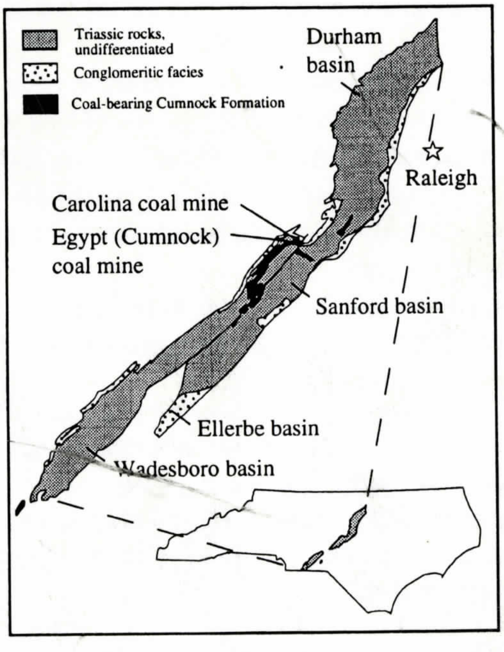
Southeastern Geology: Volume 38, No. 2
December 1998

Editor in Chief: S. Duncan Heron, Jr.

Abstract

Academic journal published quarterly by the Department of Geology, Duke University.

SOUTHEASTERN GEOLOGY



VOL. 38, NO. 2 DECEMBER 1998

SOUTHEASTERN GEOLOGY

PUBLISHED

at

DUKE UNIVERSITY

Editor in Chief:

Duncan Heron

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SOUTHEASTERN GEOLOGY is a peer review journal.

ISSN 0038-3678

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EDITOR'S PAGE

Number Four

This issue of Southeastern Geology is a theme issue edited by T. Wyche Clark. Below is his introduction.

This issue of Southeastern Geology contains four articles related to the geology of the Deep River Triassic basin, located in central North Carolina. These papers were originally presented at the Triassic Basin Initiative (TRIBI) workshop and field trip held at Duke University, Durham, NC on March 21-23, 1997.

The first of the four articles is a historical review of geological research in the Deep River basin (1820-1955). The second article discusses some of the oldest Late Triassic dinosaur footprints in North America, found in brick pits near Gulf, North Carolina. The third article presents geochemical data on many of the Early Jurassic diabase dikes that intrude the rift basin sediments. The final article contains data on several brittle fault zones immediately adjacent to the Deep River basin. These articles are but a sampling of the many basic and applied research projects presented at the TRIBI workshop.

The TRIBI workshop and field trip was held to help initiate future geologic research in the Deep River basin of North Carolina. The workshop included a multidisciplinary group of geoscientists from industry, government, and academia. In addition to an open discussion format, the organizers invited submission of oral and poster presentations concerning the geology of the Deep River basin. Topics included: stratigraphy; structure; rift evolution; paleontology; hydrology; geochemistry; geophysics; mineral resources; and brittle deformation within and immediately outside the rift basin. The field trip visited stops in the Durham and Sanford basins that expose numerous stratigraphic and structural features of diverse geologic interest. Copies of the Abstracts with Programs and Field Trip Guidebook are available from the North Carolina Geological Survey (www.enr.state.nc.us/EHNR/DLR/ncgeology/Default.htm). Link to "Publications" and then to "Field Trip Guidebooks". For more information contact TRIBI organizer - Tyler Clark (Tyler_Clark@mail.enr.state.nc.us)

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A History of Early Geologic Research in the Deep River Triassic Basin, North Carolina

T. WYCHE CLARK

North Carolina Geological Survey
Raleigh, NC 27611-7687

ABSTRACT

The Deep River Triassic basin has one of the longest recorded histories of geologic research in North Carolina. A quick perusal of nineteenth century geologic literature in North Carolina reveals the Deep River basin has received a tremendous amount of attention, second only, perhaps, to the gold deposits of the Carolina slate belt. While these early researchers' primary interests were coal deposits, many other important discoveries, observations, and hypotheses resulted from their investigations. This article highlights many of the important advances made by these early geo-explorers by trying to include information from every major geologic investigation made in the Deep River basin from 1820 to 1955. This article also provides as thorough a consolidated history as is possible to preserve the exploration history of the Deep River basin for future investigators.

INTRODUCTION

The Deep River Triassic basin (figure 1) has one of the longest recorded histories of geologic research in North Carolina. From the first published report in 1820 by Denison Olmsted, geologists have continuously been curious about the origin and timing of the basin's development. A quick perusal of nineteenth century geologic literature in North Carolina reveals the Deep River basin has received a tremendous amount of attention, second only, perhaps, to the gold deposits of the Carolina slate belt. This interest is attributed to the discovery of coal along the Deep River and the extensive efforts to determine its extent and recoverability. The majority of these investigations were performed by the North Carolina Geological Survey, and later, the U. S. Geological Survey and the U. S. Bureau of Mines. Research interest waxed and waned through the decades, prompted by periods of great economic development, destroyed by calamities such as the Civil War and the Great Depression.

While these early researchers' primary interests were the coal deposits, many other important discoveries, observations, and hypotheses resulted from their investigations. Most noteworthy is the paleontological work in the 1850's by Ebenezer Emmons, a major contributor to a

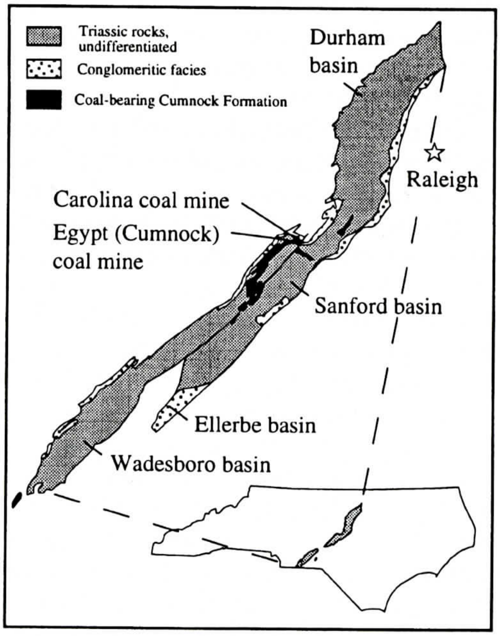

Figure 1. Simplified geologic map of the Deep River Triassic basin showing its component basins and other relevant geographic locations referred to in the text. Map modified from Bain and Harvey (1977), North Carolina Geological Survey (1985), and Olsen and others (1991).

geologic sub-discipline still in its infancy. These and many other "ahead of their time" observations will be mentioned below. The work of these early researchers gives fascinating insight into the state of the geological sciences in our country at a time when many of the geologic fundamentals we take for granted today, were considered wild speculation back then. While many of the hypotheses really were wild speculation, their basic field observations were well founded. We must keep in mind that, unlike today, these early geologists had little to no geologic foundations to rest their hypotheses on, let alone such essential equipment as topographic maps, Brunton compasses, or aerial photographs. In light of all the technological advances of our time, it is most humbling to reoccupy an outcrop visited 150 years earlier and find its position plotted correctly, and its strike and dip and lithologic description still accurate by today's standards. The level of quality and attention to detail in these early reports cannot be found in many of today's geologic journals and many an author would be well served to follow their predecessors' examples.

Figure 2. Denison Olmsted (1791-1869), Professor of Chemistry and Mineralogy, University of North Carolina at Chapel Hill, creator of first geological survey in United States, first to recognize Deep River basin sediments.

THE OLMSTED AND MITCHELL YEARS (1820-1842)

The Deep River Triassic basin was one of the earliest recognized geologic terranes in North Carolina. The first geological observation of these rocks was made over 175 years ago by Professor Denison Olmsted of the University of North Carolina at Chapel Hill (figure 2). A Yale graduate of 1813, Denison was a student of Benjamin Silliman, founder of the American Journal of Science, and Denison published several papers on the rocks, minerals, and geology of North Carolina in that journal. The first of these, published in 1820, is the first known article describing the geology of the Deep River basin. The article, entitled "Red Sandstone Formation of North Carolina" (Olmsted, 1820), is in the form of a letter (presumably to Silliman) dated February 26, 1820, and states:

"An extensive secondary formation has lately been discovered near us. On the road between this place and Raleigh, traveling eastward, we come to it four miles from the College; but at another point it has been discovered within two miles of us. It is a sand stone formation. The varieties are the red and grey. I have traced it through the counties of Orange and Chatham, and have ascertained its breadth, between this and Raleigh, to be about seven miles. Its direction is a little west of south. If a line be drawn through the Richmond bason [sic] parallel to the great mountains west of us, it will pass through this formation. Hence, must we not regard this as a continuation of the great sand stone formation, which W. McClure has traced to the Rappahannock? Must we not consider the Richmond bason [sic] and this as forming parts of the same formation? The variety found nearest to this place is not unlike the old red sand stone found in your vicinity."

Even at this early date, geologists recognized similar rocks up and down the Atlantic seaboard and were attempting to assign them to the same formation. This large-scale correlation would be the foundation of the yet to be named Newark Group. It is unclear when exactly Olmsted recognized these sediments, but not before 1817, when he was appointed to the university. The sandstone had, however, been known locally for some time, since it had been used extensively as decorative building stone in 1793 for Old East, the first campus building at the University of North Carolina.

Olmsted's letter continues: "It was natural to look for coal here and I have for some time directed the attention of my pupils, and of stonecutters to this object. Two or three days since one of the latter brought me a handful of coal, found in this range, on Deep River in Chatham County about twenty miles south of this place. The coal is highly bituminous, and burns with a very clear and bright flame. It is reported that a sufficient quantity has already been found to afford an ample supply for the blacksmiths in the neighborhood. It is my intention to employ the first leisure I can command in collecting more precise and extended information on this formation." Olmsted was apparently unaware that the coal had been known by locals for almost 50 years, but later acknowledges the fact in a report made in 1824.

The "true" discovery of coal and iron along the Deep River had apparently been made by George Wilcox, who opened a forge and bloomery in 1775 and proposed to make cannon and munitions for the Revolutionary War. "According to North Carolina Colonial Records 1775-1776, Vol. 10, pages 647-650, James Milles on July 3, 1776 wrote the Council of Safety that on the north side of the Deep River there was 'Pit coal' that appeared to be very good and in great quantities" (Stuckey, 1965, p. 512). Chance (1885) states that the discovery occurred at the site of the Horton mine where the "coal was dug from open pits for blacksmithing... but no systematic attempt was made to open the field until the slackwater improvement of the Deep River." The intended transportation route for the coal was by water to the port at Wilmington, but rapids along both the Deep and Cape Fear Rivers made boating inefficient and dangerous. Primitive locks and dams quickly failed due to limited construction technology and frequent floods, and as a result, the coal was used only for local purposes until the 1850's.

Because of Olmsted's interest in the geology and mineral resources of North Carolina, he proposed the idea of a State Geological and Mineralogical Survey to the Board of Internal Improvements in 1821. Olmsted's original request was denied by both the Board and the State Legislature in that year, but on December 31, 1823, the State legislature passed an act "... to employ some person of competent skill and science to commence and carry on a geological and mineralogical survey of the various regions of this State;..." (Stuckey, 1965). Due to his interest and experience, Olmsted was chosen as this person.

Receiving a yearly salary of $250.00, Olmsted traversed the state on horseback, collecting and describing fossils and minerals from Cape Lookout to as far west as the Great Smoky Mountains. In his first report ("Report on the Geology of North-Carolina, Part I", dated November 10, 1824), Olmsted describes the lateral extent of the basin from Oxford, NC into South Carolina with a varying width of 8 to 18 miles. Olmsted also discusses the use of sandstone for building material and the agricultural importance of the "Mill-stone grit" of Moore County. He describes the rock as "...a hard, greyish red Sand-stone, in which are thickly imbedded water-worn pebbles of white flint or quartz. These Mill-stones are very much valued for grinding, and are sought for from distant parts of the State, and bring from thirty to one hundred dollars per pair" (Olmsted, 1824, p. 15).

Olmsted also discusses coal in the area of the Deep River, and how important it would be to the public in the future, if and when timber fuel might become scarce. "Every State in a stage of progressive improvement, although at present supplied with abundant resources for fuel in her native forests, must look forward to a period when those resources will be either partially or wholly exhausted" (Olmsted, 1824, p. 17). "Although, therefore, we may now look around us and see apparently an exhaustless supply of fuel in our forests, yet the time may not be distant when some large manufacturing establishment shall call loudly for Coal; and perchance in no very distant age, the domestic wants of some portion of our citizens may make them look for this article with very different feelings from any that influence the present generation" (Olmsted, 1824, p. 18). Such insight on the future availability of natural resources qualifies Olmsted as one of the state's first conservationists.

Olmsted visited the original coal mine started by George Wilcox, but found it to be abandoned and filled with water and rubbish. He did, however, note the presence of "a finely divided Black Slate," dipping "southeast at an angle of about twenty degrees," as well as the surrounding red sandstones (Olmsted, 1824, p.19). Citing the work of William McClure, who traced the unconnected red sandstones from New England to Virginia, Olmsted stated, "... I have little doubt that both the Richmond and the North-Carolina Sand-stone belong to the same formation with that north of the Rappahannock" (Olmsted, 1824, p. 18). Thus, Olmsted expanded the known boundaries of the "New Red Sandstone" hundreds of miles further to the south.

Olmsted produced a second report the following year ("Report on the Geology of North-Carolina, Part II", dated November 1825). This report concentrated on the Coastal Plain and rocks west of the Carolina Slate Belt, and did not include a discussion on the Triassic rocks. Importantly, though, as a result of his travels he produced the first geologic map of North Carolina, dated November 1825. Although in poor condition, the map still survives at the North Carolina State Archives in Raleigh. Hand drafted with color inks, the map displays eight geologic divisions, including the Deep River and Dan River Triassic areas. This map is considered to be one of the oldest, if not the oldest, geologic map of an individual state in the United States (Cliff Nelson, U.S.G.S., oral commun., 1998).

Olmsted resigned in 1825 to take a teaching position at Yale and Elisha Mitchell, also of the University of North Carolina, assumed responsibility for the survey. Mitchell had been a classmate of Olmsted's at Yale, and the two were good friends as well as colleagues (Schoepflin, 1977). Mitchell made two additional reports to the Board of Agriculture, neither one specific to the Deep River basin. According to Stuckey (1965), "Mitchell made a determined but unsuccessful attempt to continue the work started by Olmsted as indicated by the following entry found in his diary under the date of December 28, 1827, 'The Geological Survey dies a natural death at the end of this year. There is no one who takes any interest in the business, nor, in the present state of the treasury did I find there was the least prospect in succeeding in my applications to the legislature, and therefore gave it up at once.'" While never mentioned officially as the "North Carolina Geological Survey", Olmsted's "Geological Survey" was the first geologic work performed at the public's expense in the United States, and therefore qualifies as our Nation's first geological survey.

Mitchell continued as Professor of Chemistry, Mineralogy, and Geology at the University of North Carolina and produced a general geology textbook in 1842 for use by his students. While the first 122 pages are of a generic nature, the last 18 pages are devoted to the geology of North Carolina. In the four pages concerning the Deep River basin, Mitchell reports observations on such things as the extent and topography of the basin, "small nodules of compact limestone", and the reopening of the coal beds in the late 1830's. In a discussion of the extent of the sandstones, a footnote remarks, "There is in Richmond County, between Catleges' and Mountain creeks, a body of the same kind of rocks, but whether connected with the other, or a separate and independent mass has not been ascertained" (Mitchell, 1842, p. 130). This is the first recognition of the Ellerbe basin, and its connection with the Deep River basin is still a subject of debate between geoscientists. Mitchell also discusses the controversy between William McClure, Edward Hitchcock, and Henry Rogers over the name and age of these soon-to-be-Newark sandstones of the Atlantic Coast, but avoids becoming involved with the conflict. "... I have no theory to offer in regard to the mode of formation, or opinion to express respecting its age, other than it is very old" (Mitchell, 1842, p. 133). A safe statement that no one could argue with. The textbook includes a colored state geologic map, showing more refined contacts of the Deep River basin as compared to Olmsted's 1825 map.

THE EMMONS YEARS (1851-1865)

In 1851 the State legislature reauthorized the Geological Survey with a budget of $5,000 per year. Ebenezer Emmons (figure 3), previously of the New York Geological Survey, became the first official State Geologist of North Carolina and ushered in a renewed period of research in the Deep River basin (Stuckey, 1965). Coal mining had been occurring since 1830 on the Egypt plantation (figure 1) of Peter Evans, located in the great northward bend of the Deep River. Evans sold the Egypt plantation to L. J. Houghton and Brooks Harris in 1851, with Houghton taking full ownership shortly thereafter. Houghton, in an attempt to find higher quality, unweathered coal, sank the "Egypt" shaft in 1852 to a total depth of 460 feet, encountering the main coal beds at 430 feet (Campbell and Kimball, 1923). Systematic mining began and coal was transported via rail and water to Fayetteville and Wilmington, NC. The economic importance of expanding the coal operations soon became a high priority for the Geological Survey.

Emmons spent much time trying to identify the extent of the coal, and as a result collected valuable information on the basin. In his first report to the State legislature, entitled "Report of Professor Emmons on his Geological Survey of North Carolina" (Emmons, 1852), Emmons included a 30-page section describing the basin sediments and subdivided the rocks into three divisions. This was the first recognition in the Deep River basin of an apparent tripartite stratigraphy believed common to many basins throughout the Newark Supergroup. Other important observations of Emmons' 1852 report include:

- The first discussion of the basin geometry: "The Deep River coal field is in the shape of a trough!" (Emmons, 1852, p. 119). Apparently, Emmons believed the basin to be a northeast-southwest trending syncline, with the southeastern limb "concealed beneath a thick mass of soil", presumably upper Coastal Plain sediments. Emmons hypothesized the coal should also occur in the southeastern limb of this syncline and spent much time looking (unsuccessfully) for these coal outcrops.

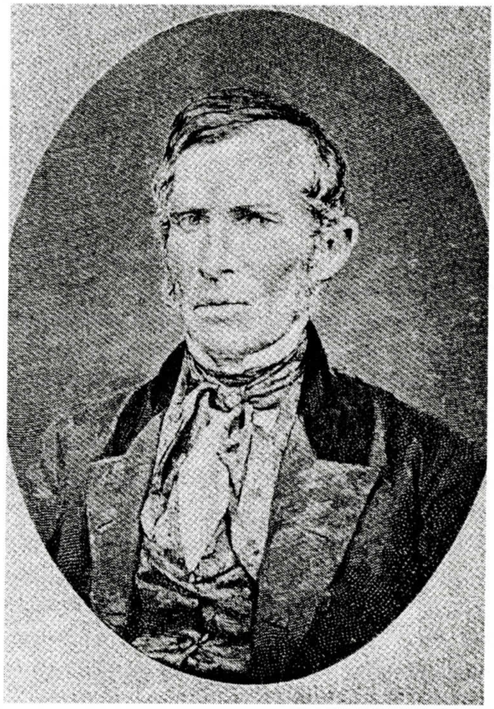

Figure 3. Ebenezer Emmons (1799-1863), North Carolina Geological Survey, paleontologist, first State Geologist of North Carolina. Photos from Stuckey (1965).

- The first estimates of the thickness of the sediments: "... the whole thickness of the formation cannot be less than five thousand feet" (Emmons, 1852, p. 137) and "The thickness which the series attain is variable; -in some it exceeds 14,000 feet" (Emmons, 1852, p. 114). Emmons' estimates were based on several measured sections; however, his estimates were most likely too high due to inadvertently measuring repeated sections caused by faulting.

- The first identification of plant and animal fossils from the basin: "...one species of molusca: a small posidonia or cypris; which is regarded as a crustacean, and which is only the size of a grass seed; the teeth of two or three saurians, and the scales of one or two fish" (Emmons, 1852, p. 140). "The presence of the cypris indicates that the slates are fresh water formation" (Emmons, 1852, p. 141). This observation apparently troubled Emmons, since he believed the upper and lower sandstones to be deposited by the ocean: "...what had been a sea became a fresh water lake (Emmons, 1852, p. 141).

• The first mention of a source area for the basin sediments: The quartz pebbles in the lower conglomerate were "derived from the neighboring rock, the gold slates" to the west (Emmons, 1852, p. 120). "The origin of these pebbles is evidently in the slates, and from the quartz seams in the slates. This rock being schistose, and largely intermixed with talc and mica, and frequently thoroughly impregnated with pyrites, is subject both to disintegration and decomposition. The quartz by these processes is then set free, or disengaged from its matrix - When exposed to the action of waves upon a beach, it is rounded and while still in the beds are subjected to pressure which results in the formation of this interesting and curious rock" (Emmons, 1852, p. 121). Again we see that Emmons hypothesized incorrectly that the upper and lower sandstones where marine in origin.

While Emmons was thoroughly familiar with the Paleozoic fossils of New England from his work at the New York Geological Survey, most of the Mesozoic fossils he collected from the coal seams were species he had not seen before, and was therefore cautious about assigning an age to the basin sediments. Citing the work of numerous authors in America and Europe (including Sir Charles Lyell), he suggested the deposits might be Permian or Triassic and related to the New Red Sandstone of Connecticut and New Jersey.

In 1856, Emmons published his "Geological Report of the Midland Counties of North Carolina". The work was a comprehensive report of the North Carolina Piedmont consisting of 351 pages, 9 plates, and 7 maps. Chapters 32 through 42 (p. 227-342) contain an expanded and revised discussion of his observations from

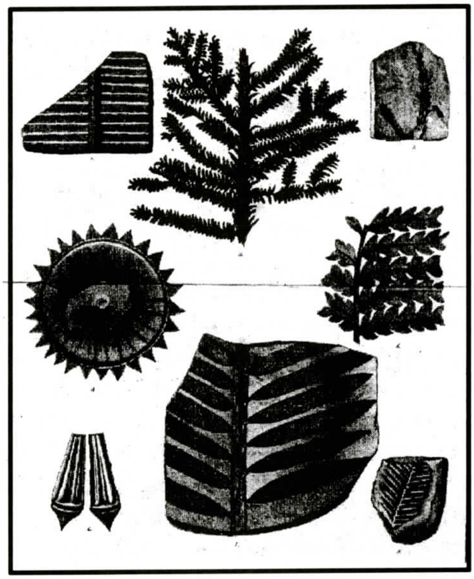

Figure 4. Illustrations of several plant fossils described by Emmons. Plate III from "Geologic Report of the Midland Counties of North Carolina (Emmons, 1856).

the 1852 report. Also included are a hand-colored geologic map of the Deep River coal field, four hand-colored cross sections of the basin, and numerous, detailed engravings of plant and animal fossils collected from the coal beds and surrounding shales (figure 4). As in 1852, Emmons divided the rocks into three subdivisions, this time suggesting ages based on fossil assemblages:

• lower red sandstone and its conglomerate (Permian);

• the coal measures, including slates, shales, and drab sandstones (Permian);

• and the upper red sandstones, conglomerates, and marls (Triassic).

The greatest contribution of Emmons, perhaps, was the description of numerous plant and animal fossils, which Emmons considered crucial in assigning an age to the basin sediments. Some of Emmons' beautifully detailed illustrations of fossil plants are shown in figure 4. Emmons documented the first fossils from the Deep River basin, which he found in the coal seams on his very first visit to the area in 1852. In all, Emmons identified about forty new species, including reptiles, fish, batrachians, and molluscs. Most noteworthy are the descriptions of the Parasuchian reptile Rutiodon and the mammal-like reptiles Dromatherium and Microconodon (Olsen, 1991). The latter two, found in the Cumnock coal mine as two, one-inch long jawbones, were considered by Emmons to be true mammals until Simpson (1926) correctly identified them as reptiles. In the same year of Emmons' second report, W. C. Redfield (1856) proposed the term Newark Group for Upper Triassic rocks in New England and included the Deep River basin into the Newark Group after a comparison of fossil samples from Emmons' collection.

In late December of 1857, North Carolina Governor Thomas Bragg requested from Emmons a special report "concerning the advantages of the valley of the Deep River as a site for the establishment of a National Foundry" with the intention of presenting the report to the United States Congress. The 14-page special report was completed in only three days. Emmons concluded the Deep River "is the most ideal spot in the county for a national foundry" based on the abundance of 1) natural resources, including coal, iron ore, timber, and building stone; 2) navigable rivers for transportation and water power; and 3) a hospitable climate, where heat and cold would not close navigation routes or interfere with the movement of machinery (Emmons, 1857). The report was apparently well received, as the following year the U.S. Senate authorized the Secretary of the Navy "to cause a thorough examination of the iron, coal, and timber of the Deep River country..." for establishment of a National Foundry (Stuckey, 1965). The purpose of this foundry would be to build engines and boilers for naval vessels. The Secretary of the Navy sent Captain Charles Wilkes and several naval engineers, who conducted their investigation in August and September of 1858. Their favorable report (Wilkes, 1858) includes: 1) a simple geologic map of the Deep River basin (from Oxford, NC to South Carolina); 2) a detailed geologic map of the coal field showing seven rock types (similar to Emmons' descriptions); and, 3) a detailed color section of the Egypt shaft to a depth of 460 feet

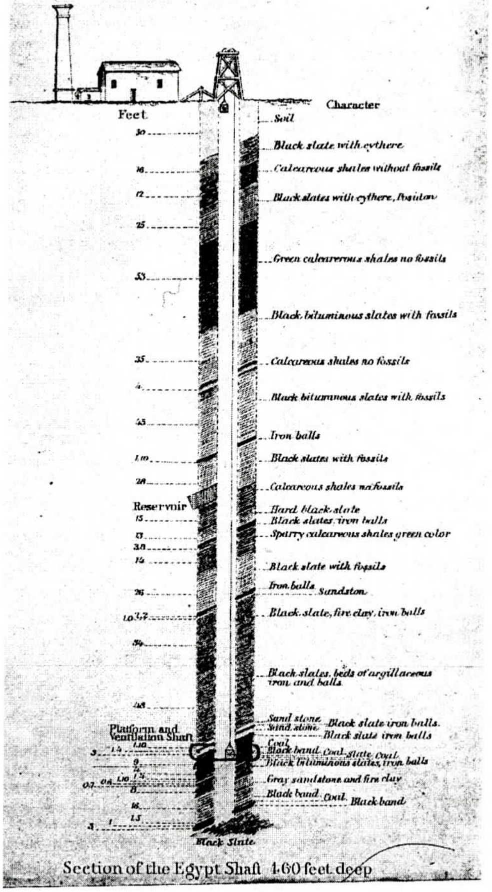

Figure 5. Geologic section of the Egypt shaft, originally opened in 1852 to a depth of 460 feet. Illustration from "Report on the examination of the Deep River district" (Wilkes, 1858).

(figure 5). It is truly fortunate that Wilkes included the color section of the Egypt shaft in his report as Campbell and Kimball remark, "The geologic world is greatly indebted to Captain Wilkes for preserving a record of the rocks penetrated by the shaft, for, so far as the writers are aware, his is the only report in which the original section was published..." (Campbell and Kimball, 1923, p. 26). Wilkes' report also cast a very favorable light on the Deep River area as a site for the foundry.

Unfortunately, the foundry was never built due to the outbreak of the Civil War. However, considerable coal was mined during the war and transported either by railroad to the arsenal at

Fayetteville or by barge to Wilmington. The coal was used primarily by the blockade runners transporting Confederate supplies through the Union blockade at Fort Fisher, at the mouth of the Cape Fear River.

During the war, the North Carolina Geological Survey was forced to change its role to strategic mineral development (i.e., coal and iron) for the Confederacy's wartime needs.

As a result, no Survey reports were produced during the war, most probably due to lack of funding. Ebenezer Emmons died on October 1, 1863, before the war's end and was buried in the City Cemetery in Raleigh, North Carolina. His body was later removed to Albany, New York. In 1864, W. C. Kerr was appointed Emmons replacement, who worked without pay to near the war's end in April 1865.

Most of the work by Emmons and his assistants was lost during the war (including mineral and fossil collections, and manuscript geologic maps of the Deep River and Dan River coal fields), presumably at the hands of Union troops, who occupied the Survey's offices in the State Capitol after the surrender of Raleigh in 1865. Many of Emmons' cataloged fossils have been found in private collections and university holdings up and down the Atlantic Seaboard. In April of 1865, the Geological Survey closed for a second time in its history. Although the Survey was restarted shortly thereafter, no detailed geologic research was published on the Deep River basin for the next 50 years.

THE POST-CIVIL WAR YEARS (1865-1920)

Geologic interest in the Deep River basin for the 50 years following the Civil War can be characterized as minimal at best. After the Civil War, work at the Egypt mine continued, but locks and dams, vital for transportation of coal to market, soon fell into disrepair. As a result, the mine closed in 1870 and was allowed to fill with water.

As part of the post-war reconstruction, the North Carolina Geological Survey was reauthorized and Professor Washington C. Kerr reappointed State Geologist. Kerr and his assistants conducted a renewed survey of the state's geographic and geologic features. Their results were published in "Report of the Geological Survey of North Carolina, Volume 1" (Kerr, 1875). Kerr and his assistants apparently did not conduct any specific investigations in the Deep River basin but Kerr does speculate on the pre-erosional extent of the Triassic rocks of North Carolina. He suggested that the Deep River and Dan River Triassic basins were part of a large, continuous formation that covered almost the entire state of North Carolina (Kerr, 1875, p.145). This sheet was then folded into a broad anticline, which was subjected to a tremendous amount of erosion, leaving the two basins today as erosional remnants over 100 miles apart. Kerr admits that based on average dips of 20-30 degrees for the basin sediments, this would require removal of over 20,000 feet of Triassic and underlying basement material in the core of the anticline, a value much higher than accepted by his contemporaries. Kerr provided no explanation for the origin of the expansive Triassic layer or the cause of the anticlinal folding. Although a large amount of erosion did take place during the Jurassic Period in North Carolina (Stuckey, 1965), there is no evidence to suggest the basins were once connected.

In 1885, Dr. H. M. Chance prepared a report for the North Carolina Department of Agriculture based on extensive prospecting and field tracing of the coal outcrops (Chance, 1885). This was the first true attempt to delineate the lateral extent and thickness of the coal through extensive field traverses and shallow auguring. Although Chance's methods of investigation were detailed and needed, his findings were not quite so favorable on the future prospects of coal mining. According to Campbell and Kimball (1923, p. 8), "Dr. Chance's conclusions were not particularly favorable." Stuckey (1965, p. 509) notes the report was "so discouraging that after publication it was withdrawn and largely destroyed."

Even in light of such negative findings, the Egypt mine was opened again in 1888 and operated minimally under the same poor mining and market conditions as in the past. After a series of gas explosions around 1902, the mine

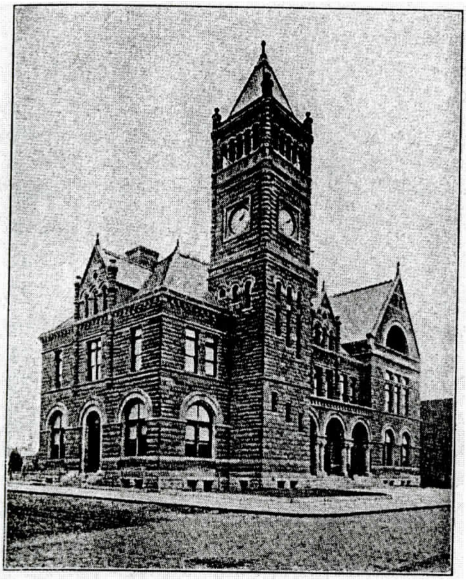

Figure 6. Old post office building in Wilmington NC built from sandstone quarried near Wadesboro, Anson County, NC. Photo from "The Building and Ornamental Stones of North Carolina" (Watson and Laney, 1906).

closed in 1905 for financial reasons. In 1915, the Egypt mine was purchased by the Norfolk Southern Railroad Company and reopened as the Cumnock Coal Company, the name Egypt being unacceptable due to its association with financial failure and disastrous explosions. Coal production, however, was small and used only by the railroad.

The 1880's to 1920's heralded a new use for the natural resources of the basin other than coal. As architectural tastes changed, so did the need for unique building stone. It was found that certain parts of the basin contained a chocolate brown sandstone, hard and massive, and ideal for building. Although quarried locally as early as the 1790's, commercial brownstone quarrying did not occur in the Deep River basin until the mid-1880's. Small quarries operated in the Durham basin, but the more important operations were in the Sanford and Wadesboro basins, specifically in Anson, Moore, Chatham, and Lee Counties (Watson and Laney, 1906). Brownstone was used extensively in public buildings in Asheville, Charlotte, Raleigh, Statesville, and Wilmington, as well as Atlanta and Baltimore (figure 6). The last recorded production of brownstone in North Carolina was in 1927 for remodeling of Holladay Hall, the original campus building at North Carolina State University in Raleigh (Stuckey, 1965).

THE ROARING '20'S (1921-1930)

The Egypt mine (now renamed the Cumnock mine) received its first major competition with the formation of the Carolina Coal Company in 1921. The Carolina mine was opened in Farmville, immediately across the river from the Cumnock mine (figures 1 and 7). To evaluate the true amount of recoverable coal reserves, the U. S. Geological Survey sent Marius Campbell and Kent Kimball to the region in the early 1920's. They published their results in North Carolina Geological Survey Bulletin 33: "The Deep River Coal Field of North Carolina" (Campbell and Kimball, 1923). Their report was prepared "with the idea that the coal is much more valuable than believed" (p. 16) and that the coal could be used for both industrial and domestic use in eastern North Carolina. In fact, the later half of their report is devoted to the promotion of the coal as being of much better quality than reported by previous geologists. The authors also believed that a comprehensive geologic investigation would assist in planning mine operations, where the lack of this data in the past had led to failure.

Campbell and Kimball made many advances in the understanding of the stratigraphy and structure of the basin, although many of their conclusions were flawed by an inadequate understanding of rift basin development, a fact that should be overlooked in light of the level of knowledge in the 1920's. Some important contributions include:

• The first real attempt to explain and predict coal outcrops through the use of structural geology: The authors explained the discontinuous map patterns of the coal beds by numerous basin-longitudinal faults (i.e., Deep River, Carbonton faults), but they still held to the idea the basin was a synclinal structure, the southeastern

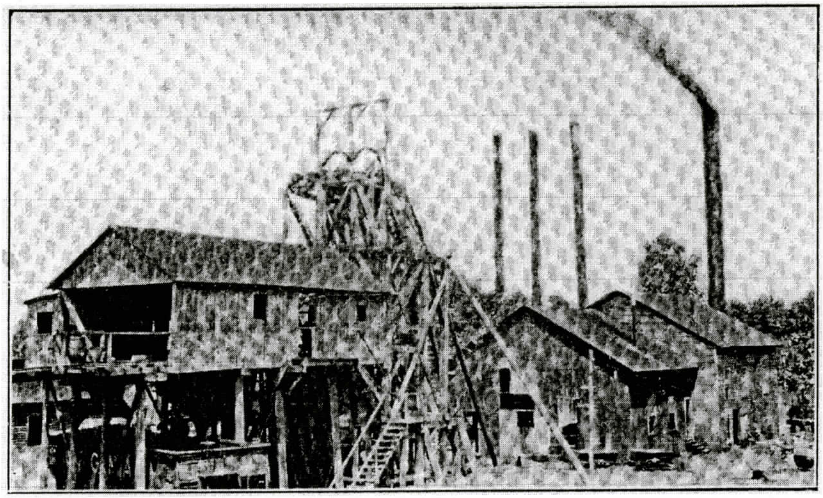

Figure 7. The Cumnock coal mine, around 1923. Photo from "The Deep River Coal Field of North Carolina" (Campbell and Kimball, 1923).

limb cut off by the Jonesboro fault. Based on a reconnaissance visit to the Wadesboro basin, they reported a true syncline was observed there with the Sanford Formation in the core and Cumnock and Pekin Formations on the flanking limbs (Campbell and Kimball, 1923, p. 49). This observation has never been verified.

• The identification and description of formal formations; the Pekin, Cumnock, and Sanford Formations: These divisions were nearly the same as those proposed by Emmons (1856), with Emmons' Coal-bearing shales and Salines being combined into the Cumnock Formation. Type localities were given for each of the formations. Although Campbell and Kimball applied these terms throughout the Deep River basin, their use today is applied only to the Sanford basin.

• The identification and description of type localities of the Jonesboro, Deep River, and Carbonton faults: Although the authors correctly identified these as basin-longitudinal normal faults (the Jonesboro with between 7,000 and 8,000 feet of estimated normal displacement), they incorrectly assumed the formation of these faults post-dated the basin infilling. This conclusion was based on the observation that the faults cross-cut all other known geologic features. While they acknowledged the concept of deposition on a subsiding surface due to faulting, the cross-cutting fault relationship led them to conclude "...that faulting did not play an important part in the original deepening of the troughs." (Campbell and Kimball, 1923, p. 61). Geologists now recognize, of course, that faulting plays a dominant role in basin sedimentation.

• Acknowledgment of the magnetism of diabase dikes: When preparing the base map for the report, using a plane-table and alidade, the authors discovered that the dikes in the area were magnetic, and had "a decided influence on the magnetic needle of the plane-table" (Campbell and Kimball, 1923, p. 12). This account is the first published acknowledgment of the magnetic anomalies of diabase dikes in the Deep River basin. The authors also point out that some dikes have an opposite sense of magnetism, thus "neutralizing the effect" of nearby normally magnetic dikes.

• Acknowledgment of the diabase dikes impact on groundwater availability: "It is interesting to note that the dikes have a very decided effect on the circulation of underground water and that this fact is utilized in the field. Thus the inhabitants have learned, through long experience, that water can be secured more readily by sinking wells near a dike than it can in the country rock where there is no dike" (Campbell and Kimball, 1923).

• Acknowledgment of diabase dikes impact on coal quality: "...the coal has been converted into anthracite wherever it has been cut by a dike" (Campbell and Kimball, 1923, p. 48). Campbell and Kimball interpreted the conversion to have taken place hundreds to thousands of feet below ground at the time of dike emplacement with great amounts of erosion now exposing the coal. "The intrusion [of dikes] must have taken place millions of years ago and probably soon after the rock-making materials were deposited." (Campbell and Kimball, 1923, p. 48). The authors, without any type of age dating, probably didn't realize how correct they were. The authors go to great lengths warning future mining operators to be wary of dikes, because of both thermal alteration and fault offsets of the coal beds.

Campbell and Kimball also briefly discuss the possibility of oil in the area. They conclude (based on faulting and dike emplacement), "...that from a geological point of view all the evidence collected in the field bearing on this question is of negative character" (Campbell and Kimball, 1923, p. 9). Although mostly confined to the Sanford basin, the work of Campbell and Kimball should be regarded as the first modern foundation of our understanding of the Deep River basin. Campbell and Kimball's report has recently been reprinted (including the geologic map) by the North Carolina Geological Survey.

Unfortunately, the spirit of renewed interest in the Deep River basin started by Campbell and Kimball was quickly extinguished in the years following their report. In 1925 a devastating gas explosion at Carolina Mine killed 53 miners, closing the mine temporarily. Finally, the Cumnock and the Carolina mines both closed in 1929 and 1930 respectively due to the Great Depression. The economic feasibility of coal mining was not regained until an event even more devastating than the Great Depression: the bombing of Pearl Harbor and the beginning of World War II.

THE WORLD WAR II YEARS (1942-1955)

The onset of World War II had a tremendous impact on the identification and development of the nation's natural resources for wartime needs. As the need for strategic minerals rose, so did the need for more basic resources such as coal for fuel. As a result, the Carolina Mine reopened in 1942. Substantial technological improvements were made to avoid the cave-ins and gas explosions that had plagued previous mine operations. It soon became apparent that a modern investigation was needed to determine the coal's extent and recoverable volume. Between 1944 and 1948, the U.S. Bureau of Mines drilled 8 coreholes totaling 11,890 feet into the Cumnock Formation. In addition, Walter Bledsoe and Company who now owned both the Carolina and Cumnock mines, drilled 11 holes in 1945-1946.

By 1949, the Carolina mine was at peak output, producing over 100 tons of coal per day. Most of this coal was purchased by Carolina Power Company who trucked the coal to its nearby steam power plant near Moncure, NC (Reinemund, 1955). As quickly as mining had resumed, however, it suddenly came to an end once more. Poorly understood faulting of coal seams and poor market conditions closed the Carolina mine in 1953. This was the last systematic coal mining in North Carolina.

Fortunately for today's researchers, most of the information gained from the coal investigations has been preserved and can be found in USGS Professional Paper 246 "Geology of the Deep River Coal Field, North Carolina", by J. A. Reinemund (1955). The 160-page report contains a thorough mining history of the area as well as technical data on the coal quality and mine conditions. In addition to the three-sheet color geologic map of the region, the report presents detailed geologic surface mapping and subsurface mine mapping of the Carolina mine, concentrating on the extent and thickness of coal, faulting, and diabase intrusions. This all-encompassing compilation still stands today as the most comprehensive report about the Deep River Triassic basin. At the time of this writing, copies were still available from both the U.S. Geological Survey and the North Carolina Geological Survey.

CONCLUSION

The Deep River Triassic basin has one of the longest recorded histories of geologic research in North Carolina. Readers of this report should have a new respect for the efforts of previous researchers to understand the complex origin of one of North Carolina's more difficult geologic terranes. Advances in geologic understanding have obviously been "spin-offs" of the geologic investigations into mineable coal reserves. As a result, these advances have been sporadic and determined by the upswings and down swings of the economy.

Most of the hypotheses of early researchers have been discarded while a few "ahead of their time" observations have survived to today. The advent of plate tectonics in the late 1960's revolutionized geologist's view of how the Deep River basin developed, and much new work has been done since then to apply these concepts to field observations. This most recent round of research is well summarized in Olsen (1991).

This article highlights many of the important advances made by early geo-explorers by including information from every major geologic investigation made in the Deep River basin from 1820 to 1955. This article provides as through a consolidated history as is possible to preserve the history of the Deep River basin for future investigators.

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SOUTHEASTERN GEOLOGY
V. 38, No. 2, December 1998, p. 77-90

THE OLDEST LATE TRIASSIC FOOTPRINT ASSEMBLAGE FROM NORTH AMERICA (PEKIN FORMATION, DEEP RIVER BASIN, NORTH CAROLINA, USA)

PAUL E. OLSEN

Lamont-Doherty Earth Observatory of Columbia University
Rt. 9 W, Palisades, NY 10964

PHILLIP HUBER

Virginia Museum of Natural History
1001 Douglas Avenue, Martinsville, Virginia 24112

ABSTRACT

An assemblage of reptile footprints from the abandoned Pomona Terra-cotta and the active Boren quarries in the middle Pekin Formation of the Sanford subbasin of the Deep River basin is the oldest track faunule recognized to date in strata of Late Triassic age in Eastern North America. The most common taxon is a possibly new genus of pentadactyl ichnite similar to, but distinct from, *Brachychirotherium*. It may lack manus impressions, has a strong tendency to be functionally tridactyl, and has an extremely shallow digit V impression. At least one track is over 30 cm in length. Also present is the quadrupedal, probably phytosaurian ichnite *Apatopus lineatus*, based on a trackway, and several small (<15 cm) bipedal and tridactyl forms that are probably dinosaurian. Other more poorly preserved forms are present. Apart from *Apatopus*, none of the tracks fit into recognized Newark ichnotaxa. The age of this track assemblage is early Tuvalian (early Late Carnian of the Late Triassic), based on associated tetrapod skeletal and macro- and micro-floral remains. This middle Pekin footprint assemblage is thus distinctly different, and older than all other Newark Supergroup footprint assemblages. It is important because it represents a transitional stage between the well known Middle Triassic assemblages and the more typically Newarkian Late Triassic assemblages. The apparently dinosaurian ichnites from this horizon are therefore arguably among the oldest in the world.

INTRODUCTION

Footprints comprise by far the most common evidence of tetrapods in the Newark Supergroup of eastern North America. They have been the subject of fairly continuous research since the first dinosaur footprint was described by Edward Hitchcock in 1836 (Hitchcock, 1836; Olsen and others, 1997), and they provide a rich source of biostratigraphic, paleoecological, behavioral, and physiological information (e.g., Olsen and Galton, 1977; Olsen, 1988; Lockley, 1991; Farlow, 1981; Farlow and Chapman, 1997). Despite the over 160 years of study devoted to Newark Supergroup tetrapod footprints, the assemblages from the Early Jurassic age strata have received most of the attention, with antecedent 30 million years of Newark track assemblages receiving relatively short shrift. Indeed, it is within only the last 45 years that the Triassic-age assemblages have been recognized as distinct in composition (Baird, 1957; Olsen and Baird, 1986; Fraser and Olsen, 1996) with most of the occurrences still being known from superficial descriptions (e.g. Olsen. 1988; Olsen and others, 1989). Here we describe the oldest known Late Triassic age footprint assemblage in the Newark Supergroup, that from the middle Pekin Formation of the Deep River Basin of North Carolina.

GEOLOGICAL PROVENANCE

The Deep River basin of North and South Carolina is the southernmost exposed of a extensive series of rift basins formed during the

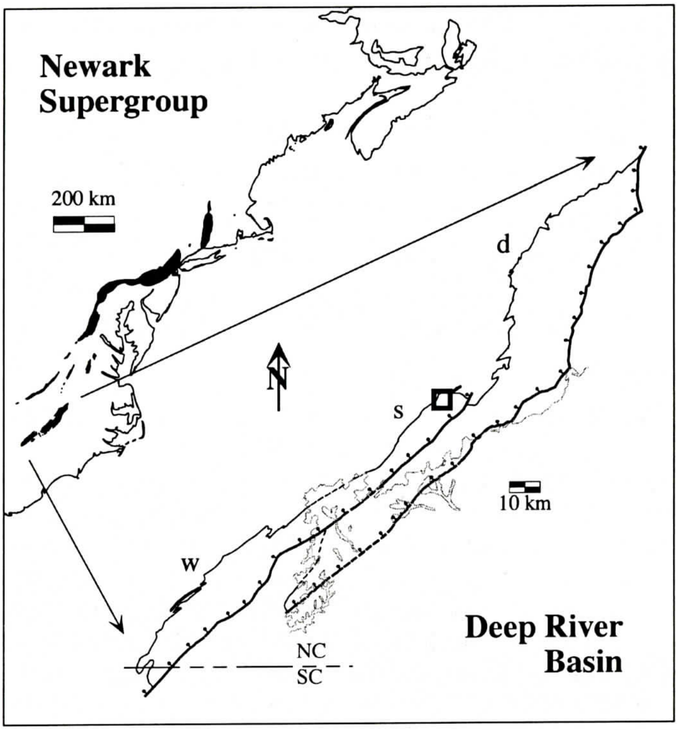

Figure 1. Deep River basin of North and South Carolina and Newark Supergroup of eastern North America. Box shows position of footprint localities (see Figure 2): d, Durham subbasin; s, Sanford subbasin; w, Wadesboro subbasin. Gray line shows limit of Coastal Plain.

Triassic and Early Jurassic break up of Pangea (Figure 1). The footprint assemblage described herein, comes from the Pekin Formation of the northern part of the Sanford subbasin of the Deep River Basin, which is the oldest formation recognized in the basin. Presently, the Pekin Formation is placed within the Chatham Group of the Newark Supergroup (Weems and Olsen, 1997) and comprises tectonostratigraphic sequence II (TS II), the oldest, widespread rift sequence in the Central Atlantic Margin rifts (Olsen, 1997).

All of the footprints described here come from two quarries called the Pomona Terra-cotta Co. quarry (now abandoned) and the Boren Clay Products quarry developed in the lower part of the middle Pekin Formation (Figure 2). As described by Reinemund (1955), the Pekin Formation in the northern Sanford subbasin, in the vicinity of these quarries, is about 530 - 550 m thick (Figure 3). Its basal beds tend to consist of about 90 m of gray or brown conglomerate and sandstone followed by mostly lenticular beds of red, brown or purple claystone, siltstone, sandstone, and locally conglomeratic arkosic sandstone. A gray sandstone and siltstone sequence is exposed near the top of the section in the main part of the Boren quarry and this interval is a marker bed mapped throughout the northern Sanford subbasin by Reinemund (1955) (Figure 2). Its position, according to Reinemund, is about 210 m above the base of the section. It is this unit that produced the well known plant assemblages described by Hope and Patterson (1969), Delevoryas and Hope, (1975), and Axsmith and others, (1995), among others. All of the footprints occur below this bed, probably within about 100 m.

Most of the footprints were found in the north end of the Pomona quarry, here termed Pomona A, during the 1970's. In Pomona A, the Pekin Formation itself consists of red bioturbated mudstone with tabular beds of ripple cross-laminated siltstone and fine sandstone (Table 1;

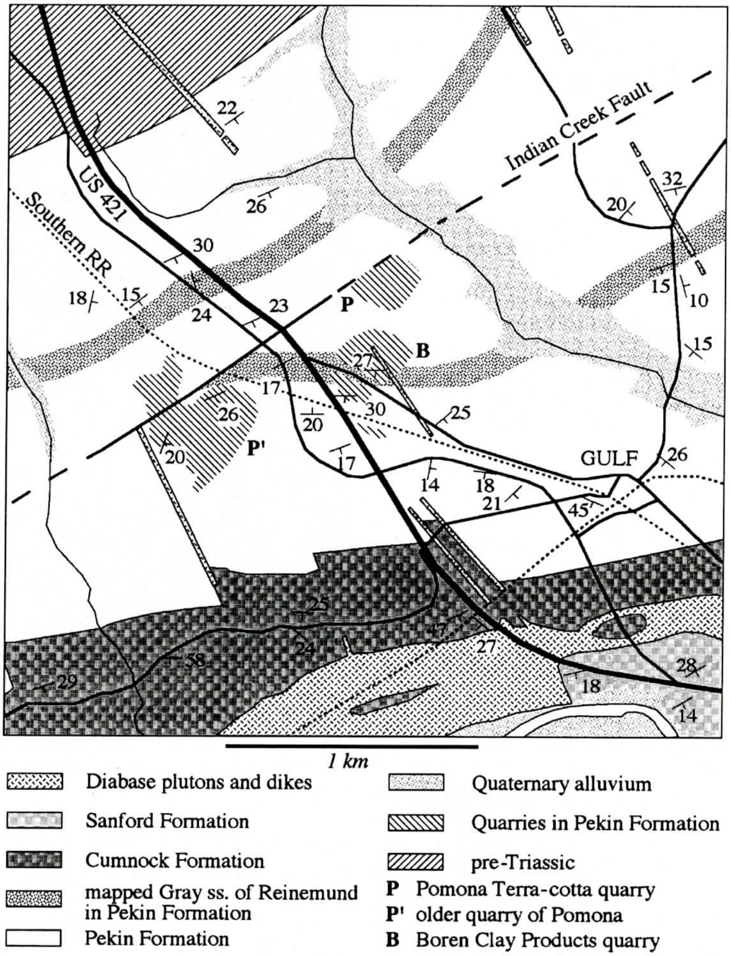

Figure 2. Map of geology in vicinity of middle Pekin Formation footprint localities. Maps are based on digitally superposed images of the U.S.G.S. 7.5 minute Goldston Quadrangles and maps of Reinemund (1955; plate 1-central, and plate 4).

Figure 4). A distinctive mudstone with plant foliage, fish scales and other fossils (Figure 5; Table 1) occurs below the main footprint-bearing unit that consists of a greenish-purple, ripple cross laminated silty sandstone. Most of the footprints from Pomona A, however were found in rubble. The important assemblage of tetrapod bones described by Baird and Patterson (1968) and Huber et al. (1993) (Table 2) apparently comes from the southern side of the Pomona quarry, here termed Pomona B. During the 1970's Pomona B was being filled in and the existing exposures did not allow for the section to be measured in detail. One track was found in 1989 in rubble from the Boren Pit.

The projected trace of the Indian Creek fault shown by Reinemund (1955) should pass through the Pomona quarry, and it should have between 100 and 250 m of normal displacement. However, a fault of this magnitude was not observed by PEO in either the Pomona or Boren quarry over 15 years of visits, and hence the fault presumably passes to the immediate east of the Pomona quarry, as it is shown in Figure 2. However, several small faults were seen in the Pomona and Boren quarries. From their narrow gouge zones, the similarity of facies on both sides of the faults, and the lack of major

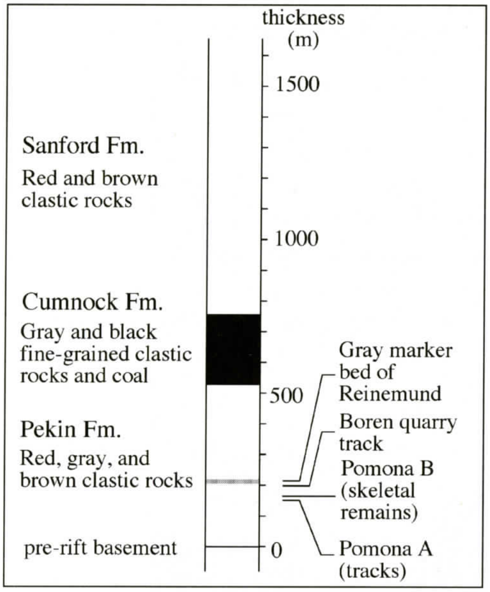

Figure 3. Section of Triassic rocks in northern part of Sanford subbasin: based on Reinemund (1955).

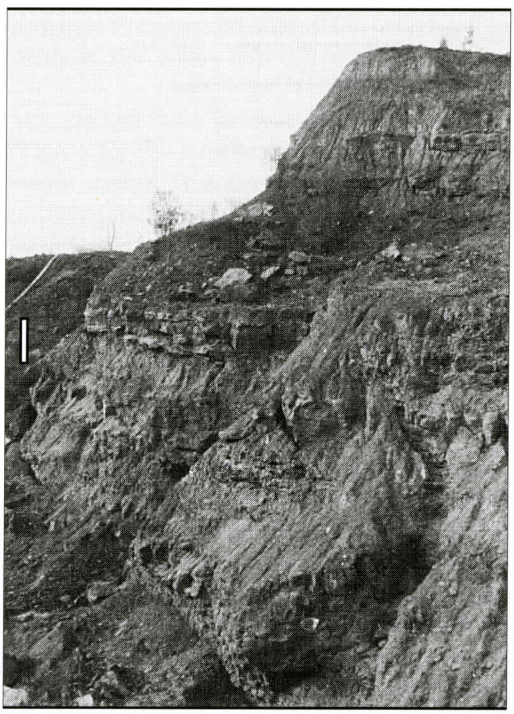

Figure 4. Exposure of footprint-bearing strata at north end of Pomona A. White bar is 1 m and is positioned just below main footprint-producing unit (Table 1).

Figure 5. Plant foliage (mostly cycadeoid) preserved as red clay films in red mudstone from within the main track bearing-unit (Table 1).

repetition of strata, these faults probably have displacements of a few meters. Unfortunately, one of these small faults separates the Pomona A section from the Pomona B section, and this and the other small faults make it impossible to compile a complete section from the plant-bearing gray sandstone marker bed in the Boren quarry through the main footprint-bearing units in the Pomona quarry, given the exposures present in the 1970's.

The tabular geometry of the footprint bearing unit in Pomona A and the presence of conchostracans in the plant-bearing strata of the Boren quarry (Olsen et al, 1989) suggests some ponded water. In combination with the presence of tilted beds of ripple-cross laminated sandstone and lenticular cross-bedded sandstones, the environment of deposition was probably shallow lacustrine, paludal, marginal lacustrine, and fluvial during the deposition of the units exposed in the Pomona and Boren quarries. The absence of caliche and evaporites and the intense bioturbation and abundant plant foliage (even in red

Table 1. Measured section at footprint-producing area on the north side of the Pomona Terra-cotta quarry. Section measured December 29, 1977. * denotes main track-bearing unit.

thickness	lithological description	fossils, other
normal fault		
+1 m	red hackly mudstone	?*Scoyenia*
0.5 m	purple-brown, green up hard siltstone	roots
0.9 m	deep purple, light purple up mudstone	hematitic nodules
0.4 m	green-purple hard siltstone and fine sandstone	footprints, roots, *Scoyenia*
3.0 m	red fissile siltstone	roots
1.0 m*	greenish-purple and red, hard, flaggy siltstone and fine sandstone	footprints, plant foliage, roots, *Scoyenia*
1.8 m	red massive mudstone, fissile upward	fish scales, coprolites, reptile teeth, plant foliage, *Scoyenia*
0.2 m	green and red, hard, massive mudstone	
1.9 m	red, greenish up, faintly lamina teconchoidally fracturing, siltstones	
+1m	green and red poorly bedded mudstone	roots, casts of *in situ* plant stems
covered		

Table 2. Vertebrate osteological remains and tracks (*) from the Pomona Terracotta and Borden quarries.

Taxon	Reference	Horizon
Synapsida		
Kannemeyeriidae		
Placerias cf. *P. hesternus*	Huber *et al.*, 1993	Pomona A
Reptilia	Baird & Patterson, 1968	Pomona A
Phytosauria		Pomona B
Phytosauria indet.		Borden
**Apatopus lineatus*	this report	Pomona B
		Borden
Archosauria		
Suchia		
Longosuchus cf. *L. meadei*	Huber *et al.*, 1993	Pomona A
Rauisuchia indet.	Huber *et al.*, 1993	Pomona A
?Suchia		
*cf. *Brachychirotherium* sp.	this report	Pomona B
?Dinosauria		
*undetermined	this report	Pomona A
		Pomona B

units) suggests persistently humid conditions.

FOOTPRINT ASSEMBLAGE

Tracks from Pomona A include *Apatopus lineatus*, abundant cf. *Brachychirotherium* spp., small three-toed dinosaurian tracks, and several unidentified forms. Most of the tracks could not be recovered and have been destroyed. A trackway consisting of a natural cast of three successive manus-pes sets on a large transported block demonstrates the presence of *Apatopus lineatus* Baird 1957 (Figure 6). According to Baird (1957), *Apatopus lineatus* is diagnosed as a

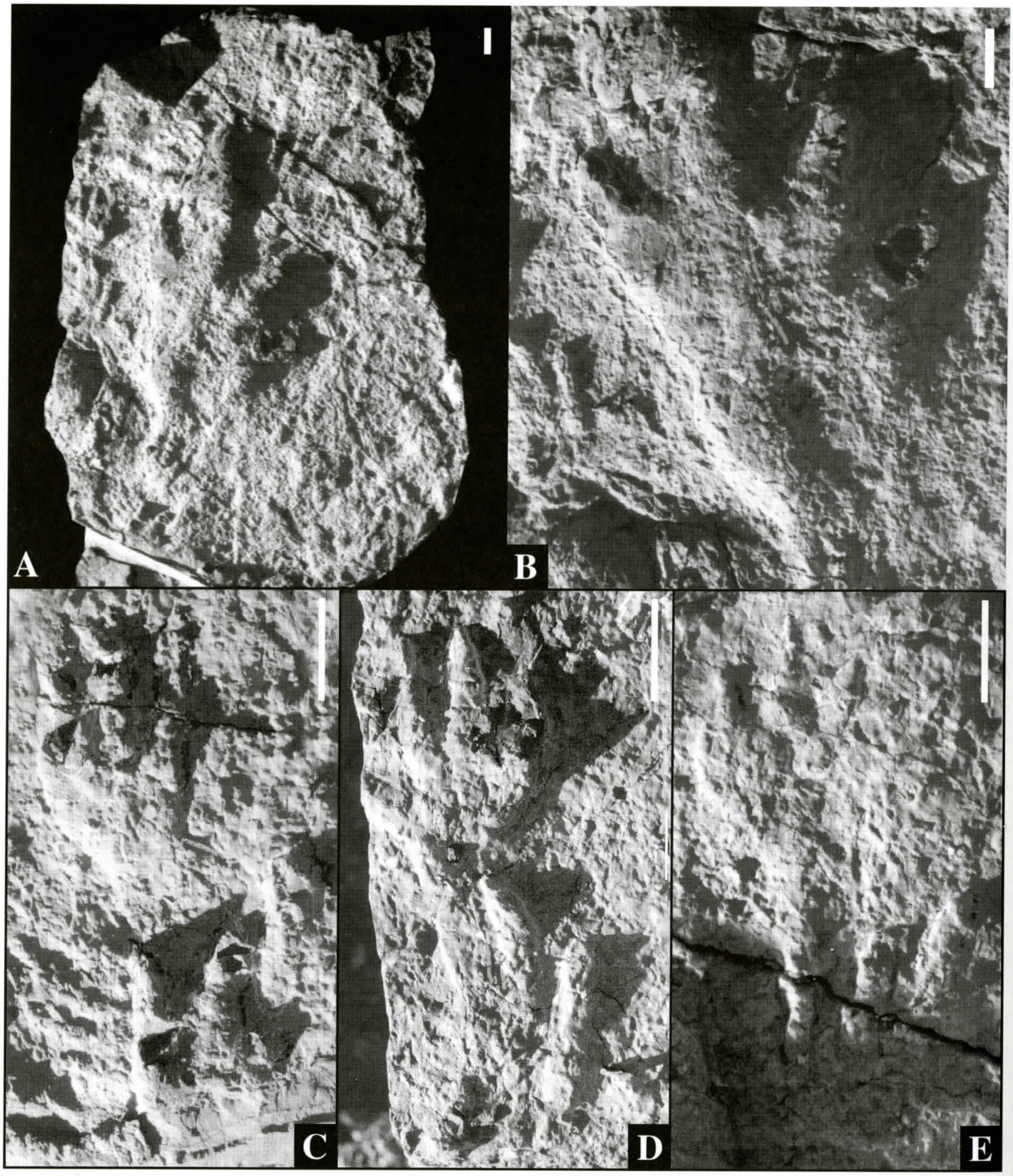

Figure 6. Large slab with natural casts of *Apatopus lineatus* and very large brachychirothere-like possible example of new genus 1; slab not collected. A, photograph of entire slab digitally corrected for parallax; B, possible example of new genus 1; C-E, successive manus-pes sets of *Apatopus lineatus*. Scale for all is 5 cm.

quadrupedal ichnite with a long, narrow pentadactyl pes with the digits in increasing length V, I, II, III, IV, and a short manus symmetrical around digit III. Usually only digits I, II, and III of the pes impress distinctly, and this is the case with the Pekin trackway (Figures 6, 7). Individual manus-pes sets (Figure 6 C-E) are indistinguishable from the type material described by Baird (1957, Plate 3, Figure 1). In addition, Baird's (1957, Figure 8) figured trackway, based on dissociated blocks, is matched closely by the Pomona trackway (Figure 7), which is

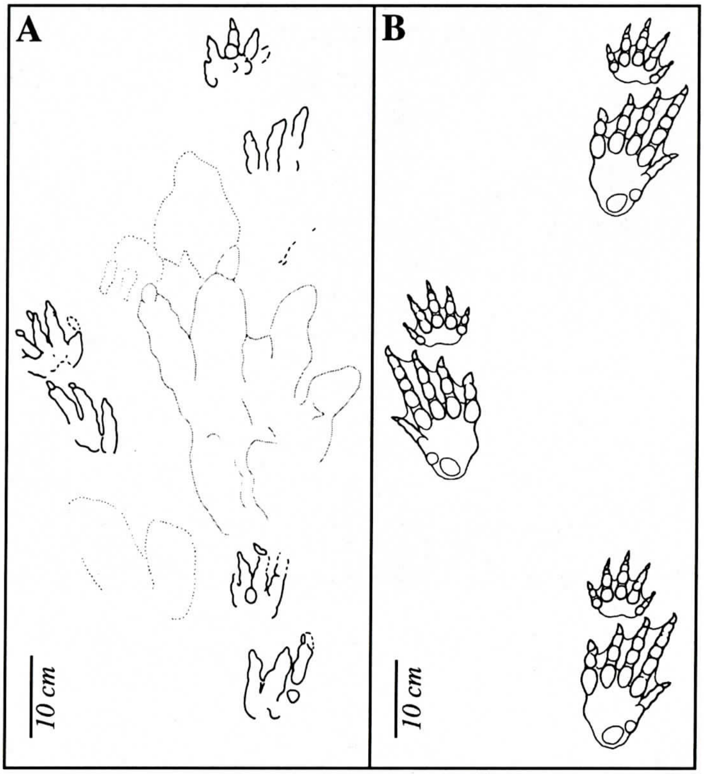

Figure 7. Outline drawing of trackway of *Apatopus lineatus* (A) compared to type trackway as reconstructed by Baird 1957 (B). B is redrawn from Baird (1957).

confirmation of his reconstruction.

Baird (1957) assigned *Apatopus lineatus* to the Phytosauria because of general similarities between the trackway of *Apatopus* and living crocodilians, the correspondence between the reconstructed skeleton of *Apatopus* and the reconstructed pes and manus, and the overlapping stratigraphic ranges of phytosaurs. Parrish (1986) has questioned this assignment on functional grounds, but has produced a forward model of a phytosaur track based on known osteology (his Figure 4.9) that is as close to *Apatopus* as can be expected given the limitations of the method. We argue that a functional argument is inherently weaker than one based on anatomical similarity, and therefore concur with Baird's (1957) original assignment.

The most abundant footprints from Pomona A are somewhat similar to *Brachychirotherium* in having a pentadactyl pes with the digit III being longest, and digit V being very reduced (e.g. Haubold, 1971) (Figures 8, 9). However, unlike *Brachychirotherium*, the impression of digit V is very weak and far posterior of its normal position (Fig 8), and digit I is small with the pes being functionally nearly tridactyl. In addition, none of the specimens from the Pekin Formation has an unequivocal manus impression. In the nearly tridactyl form of the pes and absence of a manus impression, the Pomona A forms resembles *Parachirotherium postchirotheroides* from the Gipskeuper (Early Carnian age) of Bayreuth, in Germany. As figured by Kuhn (in Haubold, 1971; 1986), however, digit V is too far anterior. As exemplified by the clearest example (Figures 8A, 9A) the track is different than any described form and probably should be named a new genus, which we call new genus 1 for this paper. However, we cannot name a new taxon at present, because, none of the specimens or casts of new genus 1 reside in institutions.

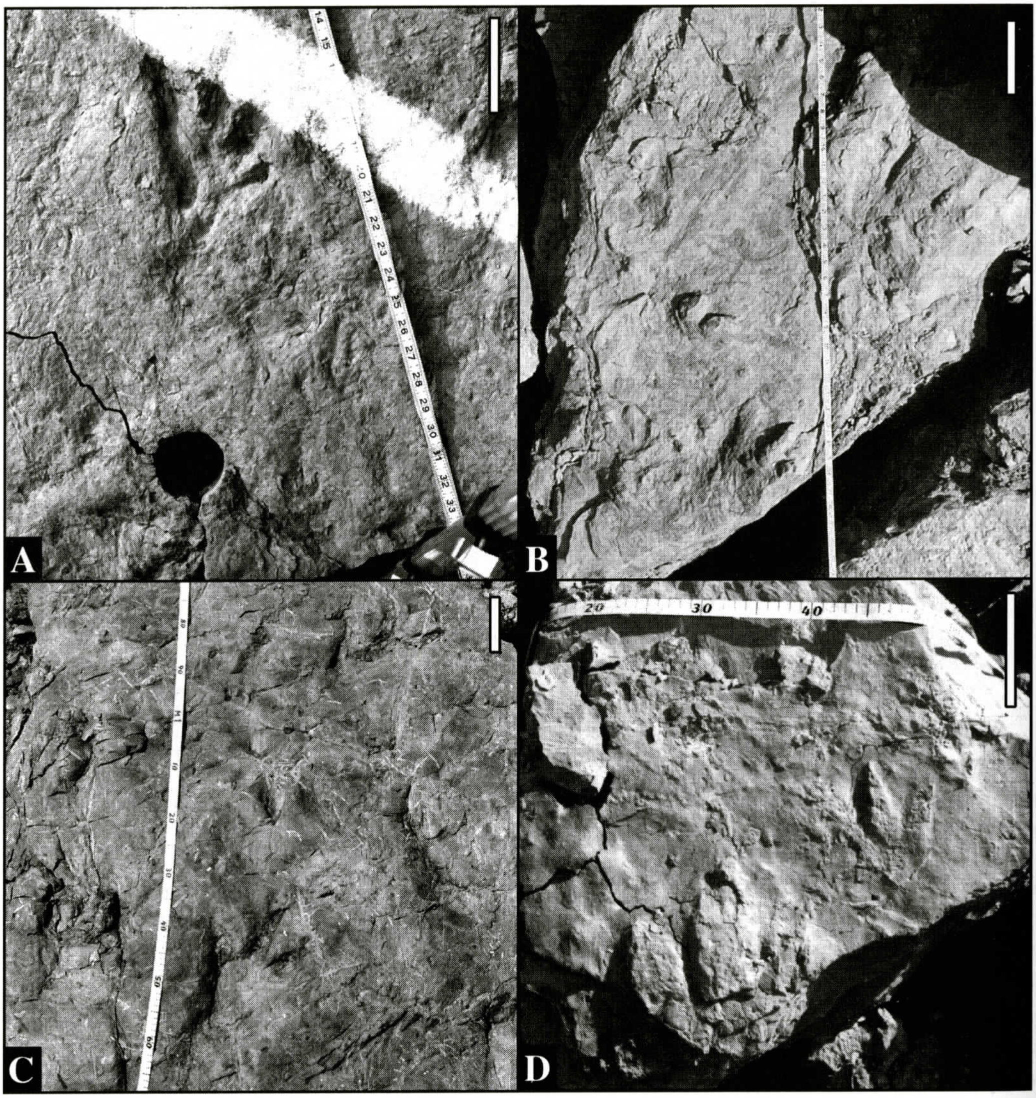

Figure 8. Slabs of footprints from Pomona A: A, new genus 1 and vague undetermined tracks (slab in collection of James L. Mashburn of Sanford, North Carolina); B, slab with natural casts of trackway of undetermined? brachychirothere with possible manus (not collected); C, large slab with deep but sloppy trackway of new genus 1 (not collected); D, natural casts of partial? brachychirothere and good dinosaurian pes (not collected). Scale for all is 10 cm.

The absence of clear pads precludes a detailed osteological reconstruction of the pes of new genus 1. However, it is clear that the track maker had a reduced digit V, a short digit I, and a long metatarsal axis. The pes skeleton of *Postosuchus kirkpatricki* (Chatterjee, 1985) is comparable to new genus 1, and it is interesting that Chatterjee has reconstructed *Postosuchus* as bipedal, which agrees with the new genus. In addition, the probably rauisuchian teeth from Pomona B could be a postosuchid. However, *Postosuchus* has a temporal range (Carnian and Norian) much greater than new genus 1 would seem to have. More track material with better defined pads is needed for rigorous analysis, however.

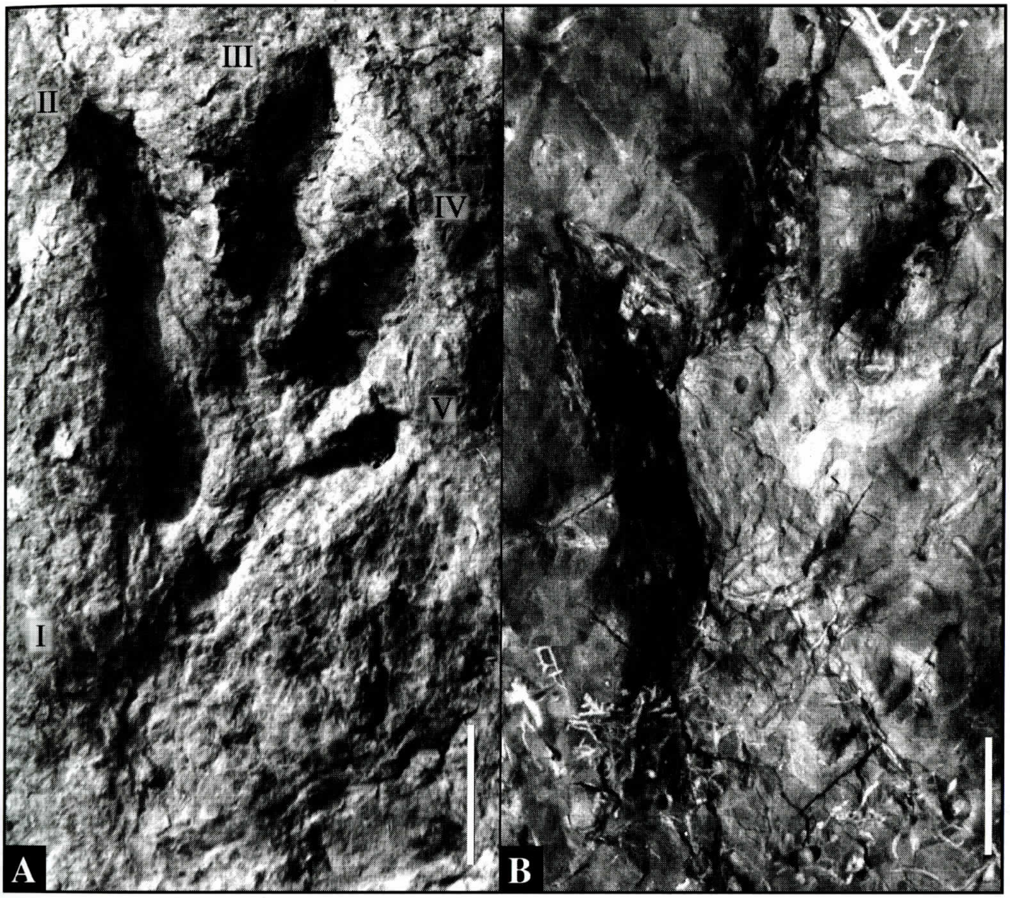

Figure 9. New genus 1: A, detail from slab in Figure 8A (note digit labels); B, detail of lower track shown in Figure 8C. Scale is 5 cm.

On the same slab as the *Apatopus* trackway (Figure 6A, B) is a natural cast of a very large (~35 cm) pentadactyl pes. Again, there is no manus impression, but this form differs from new genus 1 in having a proportionally longer digit I, shorter digit III, and more anterior and distinct digit V. Superficially the pes is comparable to large chirotheriids and brachychirotheriids (e.g. Haubold. 1971). It is possible, however, that the differences between this very large form and new genus 1 could be due to ontogenetic allometric changes similar to those seen in Early Jurassic theropod dinosaur tracks (Olsen and others, 1997). Without specimens of intermediate size, it is impossible to test this hypothesis.

Tridactyl ichnites, represented by one trackway, are present at Pomona A and the Boren quarries (Fig 8D, 10). Two of these have vague possible manus impressions, but without trackway confirmation, the association could be fortuitous. All the tridactyl forms have a widely splayed pes, with proportions and size similar to the Jurassic ichnogenus *Anomoepus* (see Lull, 1953). However, none of the Pekin tridactyl ichnites have the characteristic placement of the metatarsal phalangeal pad of digit IV directly in line with the axis of digit III. There is no sign of the distinctive pentadactyl manus of *Anomoepus* as well. The three-toed pes and bipedal trackway may be shared-derived characters of the Dinosauria. Because none of the Pekin tridactyl forms have distinct phalangeal pads we do not attempt further analysis, except to note

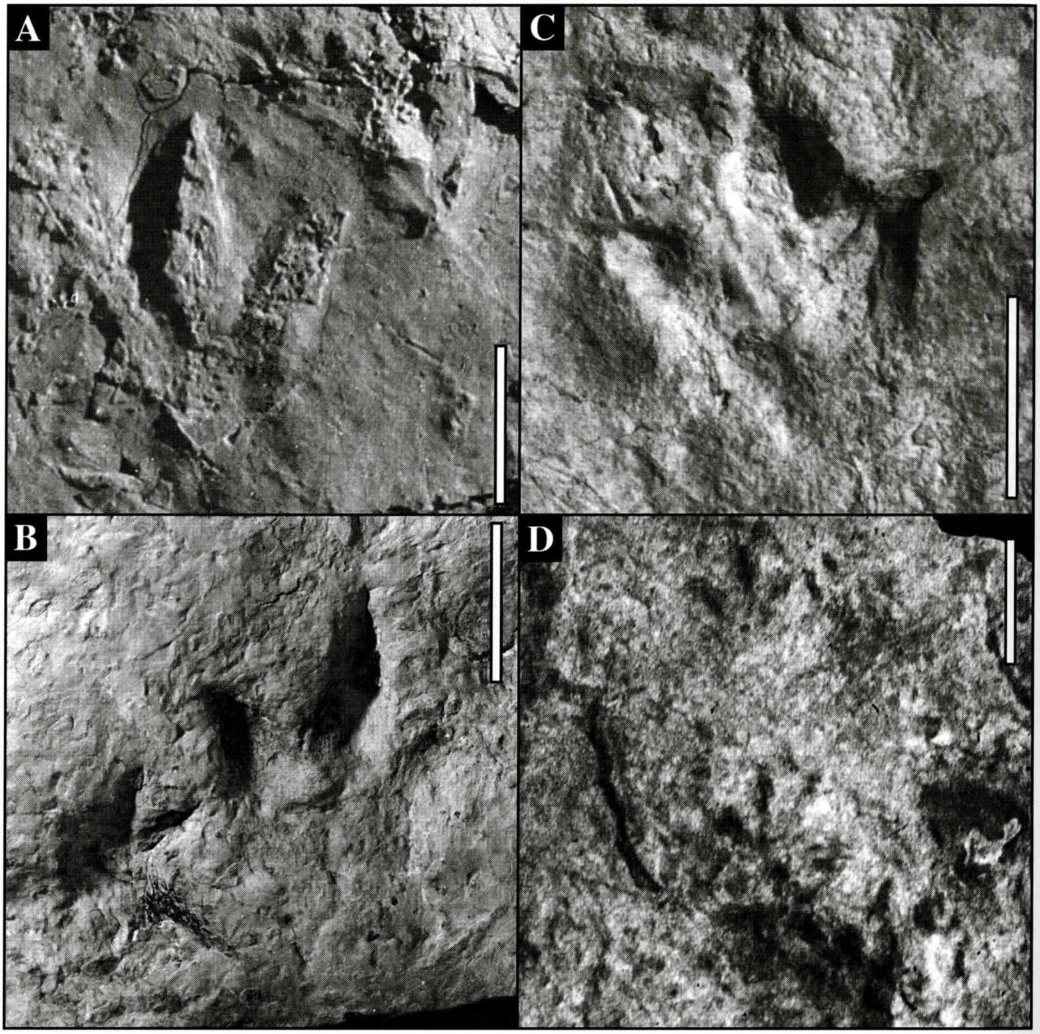

Figure 10. Dinosaurian tracks from Pomona A and the Boren quarry: A, detail of track shown in Figure 8D, right; B, pes and possible manus (Yale Peabody Museum 55875); C, natural cast of right pes from the Boren quarry (not collected); D, part of large slab of vague natural casts of dinosaurian pedes (not collected). Scale is 5 cm.

that they are plausibly, but not definitively dinosaurian.

There are a number of other traces from Pomona A that indicate the presence of other ichnotaxa (e.g. Fig 8D, left). However, these are all to poor to warrant detailed description. They indicate significant additional diversity in this assemblage.

ASSOCIATED FAUNAL AND FLORAL REMAINS AND AGE

Pomona B has produced an important although fragmentary tetrapod skeletal assemblage (Baird and Patterson, 1968). Based on the small fault offset between Pomona A and Pomona B, the footprint assemblage is no more than 40 m below the unit that produced the tetrapod assemblage, and probably significantly less. Most distinctive is the rotund dicynodont synapsid *Placerias* cf. *P. hesternus* and aetosaur scutes assignable to *Longosuchus meadi*. According to J. L. Mashburn and D. Baird (1974, pers. comm.) the *Placerias*, at least, were originally articulated specimens prior to blasting. Based on correlation with the Chinle group and the European section, these indicate an early Tuvalian (early Late Carnian) age (Huber and others, 1993). Also present are indeterminate phytosaur material and indeterminate, probable rauisuchian teeth. This assemblage comprises the type for the Sanfordian land vertebrate faunachron of Huber et al. (1993), which correlates to the Otischalkian land vertebrate faunachron of the Chinle Group of the western United States.

A palynoflorule from the basal Pekin Formation of the Sanford basin (Cornet, 1977) and the Boren quarry has produced an extensive floral assemblage (Hope and Patterson, 1969; Delevoryas and Hope, 1975; Olsen and others, 1989; Axsmith and others, 1995) that suggests correlation of the lower to middle Pekin Formation with tectonostratigraphic sequence II (TS II, Olsen, 1997) of the Richmond and Taylorsville basins. The vertebrate assemblage also suggests a correlation with TS II of the Fundy basin of the Canadian Maritimes and the Argana Basin of Morocco (i.e. Timezgadiwine Formation).

COMPARISONS TO OTHER ASSEMBLAGES

There are two accounts of footprints from the Newark Supergroup that are probably older than the Middle Pekin assemblage. The oldest is from the Honeycomb Point Formation of the Fundy basin of New Brunswick, Canada (Olsen, 1997), but these ichnites are very poor and have never been described. Shaler and Woodworth (1899) figure outline drawing of footprints from the "Productive Coal Measures" of the Richmond basin. These strata belong to the lower part of TS II and are probably older than the footprint assemblage from the middle Pekin. The drawings are, however, inadequate for comparison to other tracks and the whereabouts of the specimens is unknown.

Abundant and diverse footprint material has been recovered from tectonostratigraphic sequence III (TS III) in many other Newark Supergroup basins. Nonetheless, the only undoubted member to the Pekin footprint assemblage shared by younger Newark Supergroup faunules is *Apatopus lineatus*. The oldest assemblage that has been described in TS III is that from the upper Stockton and lower Lockatong Formation of the Newark basin of New York, New Jersey, and Pennsylvania (Olsen and Flynn, 1989; Olsen, 1988; Baird and Olsen, 1986) and the roughly coeval tracks from the Cow Branch Formation of the Dan River basin of North Carolina and Virginia (Olsen and others, 1978; Baird and Olsen, 1986; Fraser and Olsen, 1996). All of these are Late Carnian (late Tuvalian) in age and are associated with tetrapod skeletal taxa of the Conewagian land vertebrate faunachron (Huber and others, 1993). The Late Carnian age assemblages are basically the same as early and middle Norian assemblages (also in TS III) that are known from many localities and many Newark Supergroup basins (Baird, 1954; Baird, 1957; Olsen and Baird, 1986; Olsen, 1988; Olsen et al; 1989). These are dominated by *Brachychirotherium*, *Apatopus*, *Rhynchosauroides* and dinosaurian taxa, notably *Atreipus* and *Grallator*, and are associated with skeletal forms of Neshanician and lower Cliftonian land vertebrate faunachrons (Huber and others, 1993).

Otischalkian strata of the Chile Group have produced very little footprint material (Lucas and Huber, 1997) and the younger Chinle assemblages have nothing in common with the Pekin track faunule. A greater diversity of footprints is known from the European lower Keuper (km1-km3), notably with the lower Gipkeuper (km2) that produced *Parachirotherium postchirotheroides*.

The Argana and Ourika basins of Morocco have also produced a poorly known assemblage of footprints, which at first glance appears potentially similar to that from Pomona A (Biron and Dutuit, 1981). *Apatopus lineatus* appears to be present in the Ourika basin (Biron, 1981) along with tetra-or pentadactyl tracks (*Quadridigitatus dubius* of Biron) and a few unnamed tridactyl forms. Biron named two tri- tetra-or pentadactyl tracks, *Tridactylus manchouensis* and *Anomoepus moghrebensis*, that were recovered from the Timezgadiwine Formation of the Argana basin (comprising TS II of Olsen, 1997). These could be poorly preserved examples of new genus 1, however restudy and collection of new material is clearly needed. The age of the Timezgadiwine Formation is early Tuvalian (Late Carnian) and that of the tracks in the Ourika basin is constrained only to Carnian on the basis of pollen and spore assemblages (Cousminer and Manspeizer, 1976).

IMPORTANCE OF THE PEKIN ASSEMBLAGE

The footprint assemblage from the Pekin Formation of the Deep River basin is the oldest in eastern North America that is based on material good enough to analyze. Coming from strata of early Tuvalian age, it is the same age as the oldest known dinosaurs (Lucas and Long, 1992; Lucas and Huber, 1997). King and Benton (1996), suggest that all published records of dinosaur footprints of Middle Triassic age are doubtful, and therefore the tracks of dinosaurian aspect of the Pekin assemblage are among the oldest in the world. That said, it is also true that since both saurischians and ornithischians are present in late Tuvalian age strata, early Tuvalian, or even late Middle Triassic age dinosaurs plausibly existed. In addition, the feet of the earliest known dinosaurs, such as *Herrerasaurus*, retain very primitive proportions with both long digits I and IV (Novas, 1993). Therefore, it is likely that it may be quite difficult to recognize the pes of very early dinosaurs because they might resemble a brachychirothere more than a *Grallator*.

Newarkian late Tuvalian (Late Carnian) to late Norian age track assemblages are well known and could even be called stereotypical. They differ substantially from Middle Triassic age footprint assemblages described by Demathieu (1970), Demathieu and Gand (1972), and Demathieu and Weidmann (1981) in having abundant unquestioned dinosaurian tracks and a broader range of quadrupedal ichnites. The middle Pekin faunule is intermediate in age and composition between the much better known Middle Triassic and late Triassic assemblages, and is thus critical to an understanding of the origin of dinosaur-dominated communities of the later Mesozoic. For this reason, a concerted effort should be made to collect more and better material from this key interval, especially from active quarries.

ACKNOWLEDGMENTS

We are extremely grateful to the owners of both the Pomona Terra-cotta and Borden Clay Products quarries for access to their sites for over twenty years. We also thank Mr. James L. Mashburn for information on Pomona B skeletal remains and for permission to photograph his private collection. We acknowledge Hans Sues for help with comparisons to Europe. Amy Litt, Gustav Paulay, Robert Salvia, Richard Upright, and Allen Wells are thanked for help in the fieldwork from 1971 to 1977. I am grateful for a review of the manuscript by Annika K. Johansson which substantially improved it. Fieldwork during the 1970's for this paper was supported by funds supplied through Keith S. Thomson and John H. Ostrom then of Yale University whom PEO warmly thanks. This paper was supported by National Science Foundation grant ATM 93-17227 and funds from Lamont-Doherty Earth Observatory. This is Lamont-Doherty Earth Observatory contribution 5853.

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SOUTHEASTERN GEOLOGY
V. 38, No. 2, December 1998, p. 91-102

COMPOSITIONAL PATTERNS FOR LOWER MESOZOIC OLIVINE THOLEIITIC DIABASE DIKES IN THE DEEP RIVER BASIN, NORTH CAROLINA

PAUL C. RAGLAND

STEPHEN A. KISH

WILLIAM C. PARKER

Department of Geology and National High Magnetic Field Laboratory
Florida State University
Tallahassee, FL 32306

ABSTRACT

Among 56 screened analyses from a large number of chemical analyses for Lower Mesozoic diabase dikes in the Deep River basin, North Carolina, two compositional groups exist: a main group (41 samples) and a high-Fe group. All rocks are either aphyric or olivine ± plagioclase phyric. Compositions of the high-Mg members of the main group approach those of primary picritic magmas. Trends on variation diagrams and least-squares mixing calculations for the main group indicate that the most differentiated sample can be derived from the least differentiated (high-Mg picritic, assumed to be primary) by low-pressure fractionation (35 percent) of about 2/3 olivine and 1/3 plagioclase.

Chondrite-normalized rare-earth element and spider diagram patterns are generally flat, with slight large-ion lithophile (LIL) element enrichment (10-20 times chondritic abundance; no Eu anomalies). Patterns most closely resemble those for E-MORBs, except for positive Ba-K and negative Nb anomalies. Despite their rift-related continental emplacement, compositions of these dikes plot in the MORB field on tectonic discrimination diagrams. However, their isotopic compositions are in the "enriched" field on a Sr-Nd correlation diagram. On a $^{206}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ diagram, the diabase trend approximately parallels the MORB trend, but at higher $^{207}Pb/^{204}Pb$. The isotopic evidence indicates that the Deep River diabases are from a mantle source that, relative to MORBs, had long-term enrichment in incompatible elements such as U and Rb, or represent crustal contamination of a MORB-like magma.

Thus despite some chemical similarities to MORBs, isotopic evidence indicates a mantle source different from those producing MORBs. This diabase source might include old lithospheric components, either related to contamination of continental crust or contribution of Grenville subduction-related slabs to the mantle source. Finally, correlations among MgO-standardized $Na_{8.0}$, $Fe_{8.0}$, and $Si_{8.0}$ in MORBs on a "local" (rather than "global") scale are quite similar to such correlations shown by the Deep River diabases. The Deep River diabase magmas may therefore have been formed by a mechanism similar to that which apparently formed MORBs, whereas relative to magmas of the main group, those of the high-Fe group represent a deeper source and smaller degree of melting.

INTRODUCTION

Most diabase (dolerite) dikes in the Triassic Deep River basin, North Carolina, belong to the swarm of NW-striking dikes that extends from northern Virginia to Georgia within the Lower Mesozoic eastern North America (ENA) mafic petrographic province (Daniels and others, 1983; de Boer and others, 1988; Ragland and others, 1992). The dikes may have been feeder dikes for flood basalts since eroded away, as proposed for flood basalts of the same age in northeastern North America (McHone, 1996).

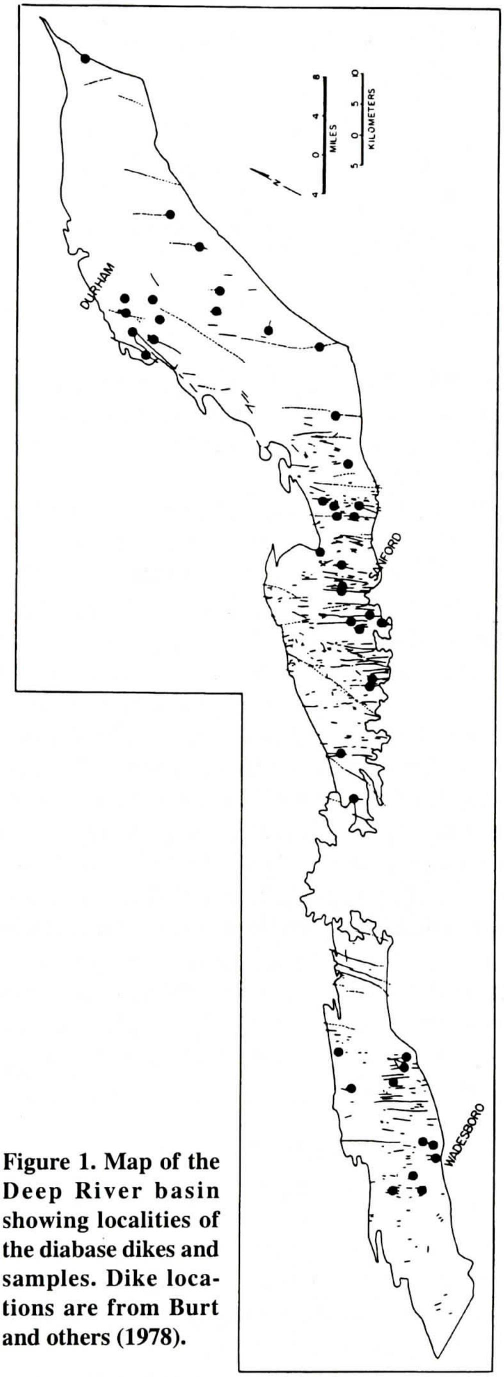

Figure 1. Map of the Deep River basin showing localities of the diabase dikes and samples. Dike locations are from Burt and others (1978).

The dikes, along with other circum-Atlantic Lower Mesozoic mafic rocks, are associated with the late-rifting, early-drifting stage of the Pangaean breakup (ibid.). All the Lower Mesozoic circum-Atlantic mafic rocks, present on four continents (North America, South America, Africa, Europe; May, 1971; Cummins and others, 1992), were emplaced around 200 Ma ago, but the exact time span has not yet been determined. Weems and Olsen (1997) reported that a "discrete interval of synchronous or nearly synchronous" mafic igneous activity occurred throughout the early Mesozoic rift system of eastern North America. Sutter (1985, 1988; personal communication, 1992) obtained reliable Ar-Ar plateau ages of around 200 Ma for ENA rocks from North Carolina northward to New England.

This paper primarily deals with the geochemistry of the Deep River diabase dikes. These dikes crosscut all the Triassic rocks and the border faults of the basin. The Deep River Basin rests upon a thick sequence of crystalline rocks the comprise the Carolina terrane, a Late Proterozoic-Early Paleozoic mature arc. The Carolina terrane is thought to be allochthonous with respect to underlying Grenville-age crust (Samson and others, 1995).

Fifty-six screened analyses were compiled from 200+ chemical analyses of diabase dikes in the Deep River basin; diabase and gabbro sills in the basin are not included in this study. In addition, dike samples that are altered, contain abundant cumulus phases, or have inferior and/or anomalous analyses were not chosen, and only one or two representative samples were taken from transverse profiles across any dike. Only 44 of the reported sample localities were sufficiently specific to be shown on Figure 1. Sources for data are Ragland and others (1968), Ragland and others (1971), Weigand (1970), Drez (1977), Whittington (1988), Pegram (1986), and unpublished analyses from D. Gottfried (1994). All the samples included in this study are olivine normative and modal; they are aphyric or olivine ± plagioclase phyric. Groundmasses vary from isogranular to subophitic; classic diabasic texture, with plagioclase chadacrysts partly or wholly enclosed by augite oikocrysts, is very common.

The main purpose of this paper is to examine trace-element, major-element, and isotopic compositional patterns for the Deep River dia-

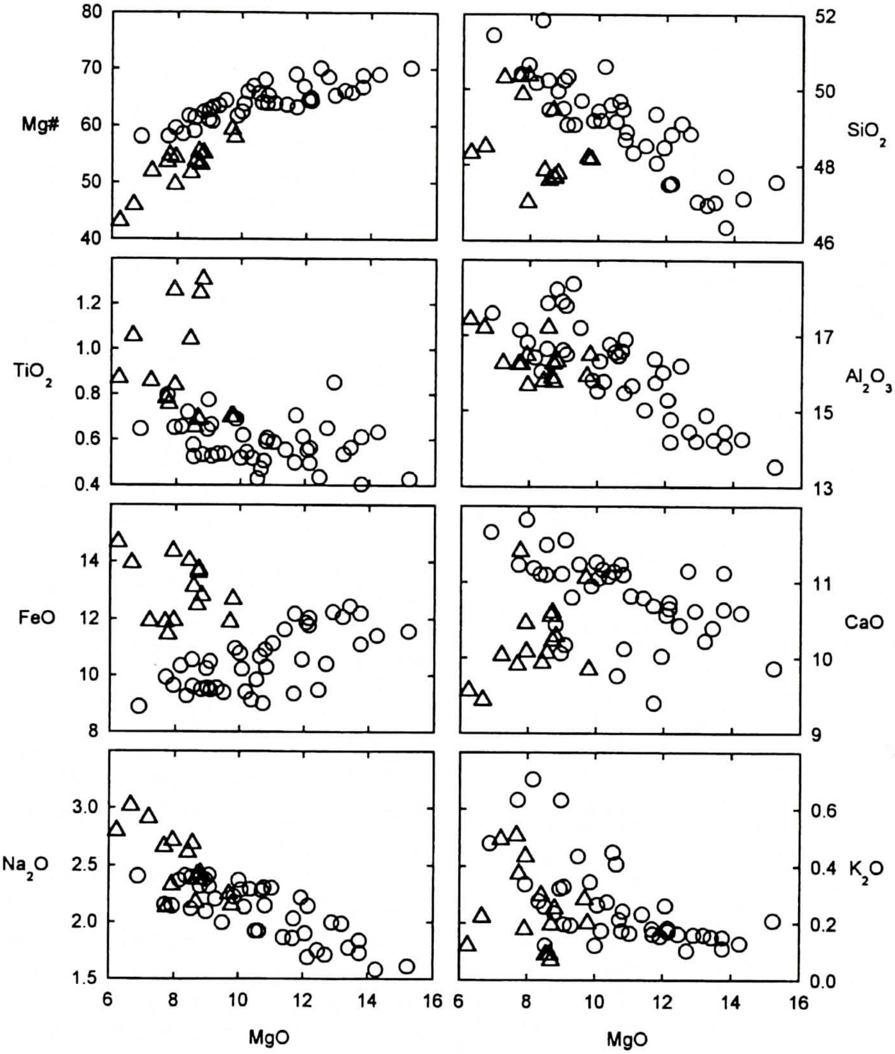

Figure 2. Major-element Fenner diagrams for Deep River diabase dikes. All analyses in weight percent. The main trend on this and subsequent diagrams is denoted by circles and the high-Fe group by triangles.

base dikes and to compare them to other mafic igneous suites. In particular, we emphasize their similarities and dissimilarities to mid-ocean ridge basalts (MORBs). Several workers in this laboratory have compared these rocks with MORBs (e.g., Ragland, 1991; Ragland and others, 1992; Ragland and others, 1983; Cummins, 1986), and this paper will carry this comparison one step further.

RESULTS

Two compositional groups exist for the Deep River basin dikes: a main group (41 samples) and a minor group (15 samples), referred to herein as the "high-Fe group" (Fig. 2). Whittington (1988, 1989) referred to high-Fe olivine diabases from North Carolina as the HFO (high-Fe olivine) group; the main group as defined in this paper is approximately equivalent to his LFO (low-Fe olivine) diabases (see Ragland

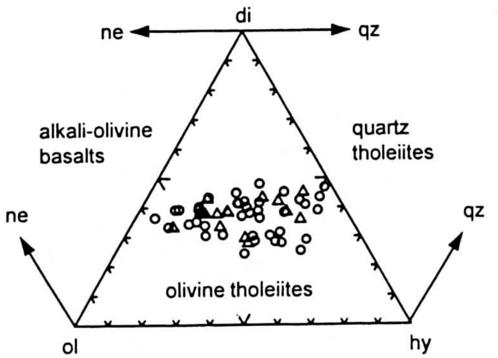

Figure 3. Normative olivine-diopside-hypersthene (ol-di-hy) projection of the basalt tetrahedron for the Deep River diabase dikes.

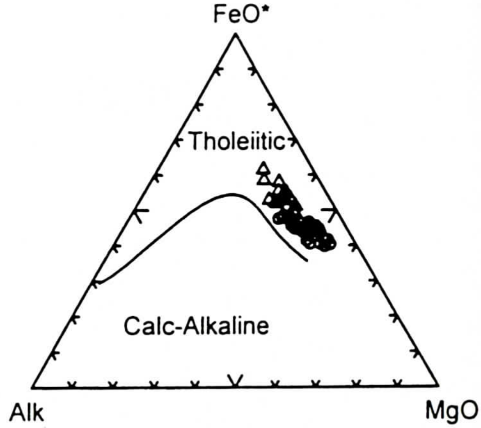

Figure 4. AFM diagram for the Deep River diabase dikes. A = alkalies = $Na_2O + K_2O$; M = MgO; F = FeO* = total Fe as FeO.

and others, 1992, for a discussion of the various classifications of ENA diabases). Other element compositions are systematically different between the two groups (Fig. 2 and Table 1). For example, compared to the main group, the high-Fe group is generally characterized by higher incompatible-element and lower compatible-element abundances. Normative mineral proportions of the two groups are similar (Fig. 3). All samples are classified as olivine tholeiites (Fig. 3) and their compositions plot on a classic tholeiitic trend of Fe-enrichment (Fig. 4); obviously, compositions of samples in the high-Fe group plot at the high-Fe end of this trend. Some main-group rocks (the MgO-rich samples) approach picrites in composition; these rocks have Mg numbers (Mg#) of ~70 (Fig. 2). Magmas from the most aphyric of these Mg-rich picritic samples were probably mantle equilibrated and thus compositions of these rocks probably represent primary magmas.

Table 1. Means and standard deviations for chemical analyses from the Deep River diabase dikes (olivine tholeiites; oxides are in weight percent; trace elements are in ppm).

	hi-Fe			main		
	mean	std. dev.	n	mean	std. dev.	n
SiO_2	48.61	1.10	15	49.03	1.24	41
TiO_2	0.90	0.22	15	0.58	0.10	41
Al_2O_3	16.34	0.53	15	16.02	1.24	41
FeO*	12.97	1.01	15	10.51	1.04	41
MgO	8.19	0.96	15	10.73	1.97	41
CaO	10.23	0.51	15	10.79	0.53	41
Na_2O	2.51	0.28	15	2.09	0.24	41
K_2O	0.25	0.14	15	0.26	0.15	41
P_2O_5	0.14	0.05	4	0.10	0.02	16
Ba	218	66	7	120	43	22
Co	71	12	9	61	8	18
Cr	335	141	12	631	297	27
Cu	149	26	12	109	14	19
Hf	--	--	--	1.24	0.18	22
Nb	--	--	--	2.63	0.53	8
Ni	222	85	12	315	115	27
Rb	7.6	4.0	9	6.1	3.7	31
Sb	--	--	--	1.58	0.69	13
Sc	--	--	--	38.9	3.2	17
Sr	140	40	12	118	31	34
Ta	--	--	--	0.14	0.03	17
Th	--	--	--	0.38	0.12	16
V	193	14	7	182	16	23
Y	25	8	7	15	4	15
Zn	92	8	12	78	9	27
Zr	60	23	12	45	12	34
La	--	--	--	5.44	1.46	19
Ce	--	--	--	11.3	1.8	24
Nd	--	--	--	5.70	1.06	27
Sm	--	--	--	1.90	0.34	27
Eu	--	--	--	0.66	0.12	24
Tb	--	--	--	0.60	0.16	17
Yb	--	--	--	2.54	0.42	24
Lu	--	--	--	0.43	0.08	24

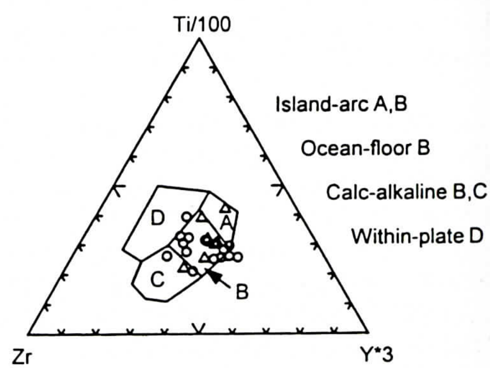

Figure 5. Ti-Zr-Y tectonic discrimination diagram (after Pearce and Cann, 1973) for the Deep River diabases.

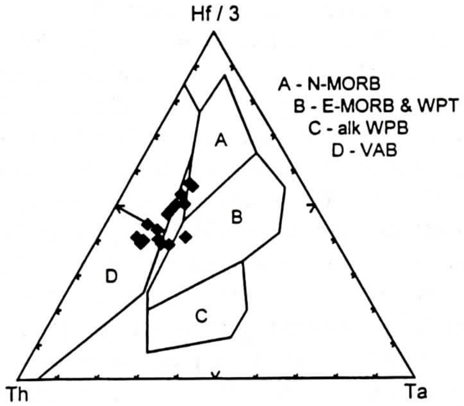

Figure 6. Hf-Th-Ta tectonic discrimination diagram (after Wood, 1980) for the Deep River diabases.

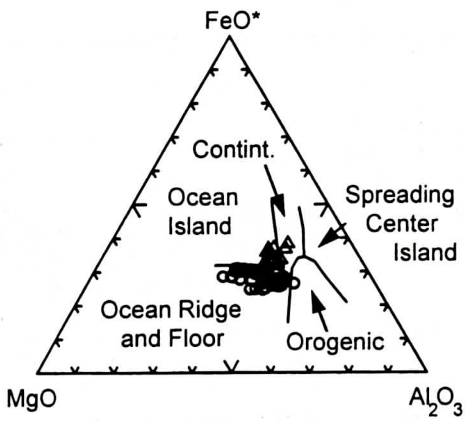

Figure 7. MgO-FeO*-Al_2O_3 tectonic discrimination diagram (after Pearce et al., 1977) for the Deep River diabases.

Chemical trends on Figure 2 and least-squares mixing calculations for the main group indicate that in terms of major elements, the most differentiated (lowest MgO) sample can be derived from the least differentiated (highest MgO, assumed to be a picritic primary melt) by low-pressure (crustal) fractionation (35 percent) of about 2/3 olivine and 1/3 plagioclase. Phenocrysts present are either olivine or plagioclase, thus both the major-element trends and the petrography indicate a low-pressure olivine-plagioclase extract assemblage for the main-trend rocks.

Figures 5-7 are tectonic discrimination diagrams. Although the dikes were almost certainly emplaced into attenuated continental lithosphere, this is not apparent from Figures 5-7. The Deep River diabases clearly have more affinities with MORB or arc tholeiites than they do with within-plate (including continental) basalts (Figs. 5-7). This observation has been made for the ENA petrographic province in general (Gottfried and others, 1977; Philpotts, 1985; Ragland and others, 1992). As Duncan (1987) pointed out, however, compositions of many continental tholeiites do not plot within their proper fields on tectonic discrimination diagrams such as those shown in Figures 5-7.

Chondrite-normalized rare-earth element (REE) and spider-diagram patterns for the dikes are generally flat (Fig. 8A), with slight LIL enrichment; values average 10-20 times chondritic abundance with no Eu anomalies. A negative Nb and Ta anomaly is apparent on Figure 8B,

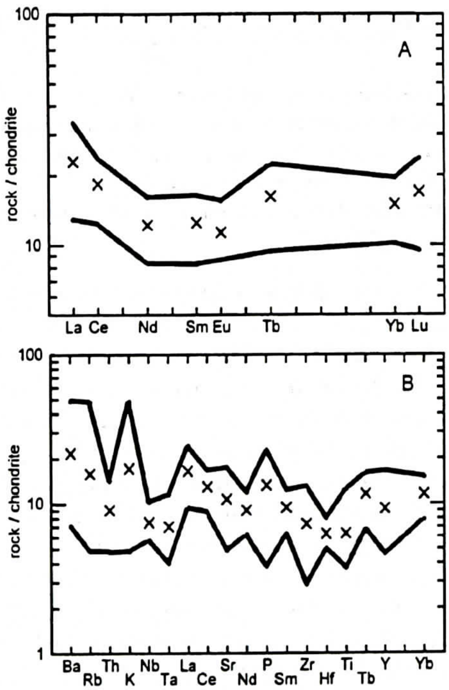

Figure 8. Spidergrams normalized to chondrites for (A) rare-earth elements, and (B) all incompatible elements from the Deep River diabases (normalizing factors from Thompson, 1982). Sources for data are given in the text. Averages are denoted by X's.

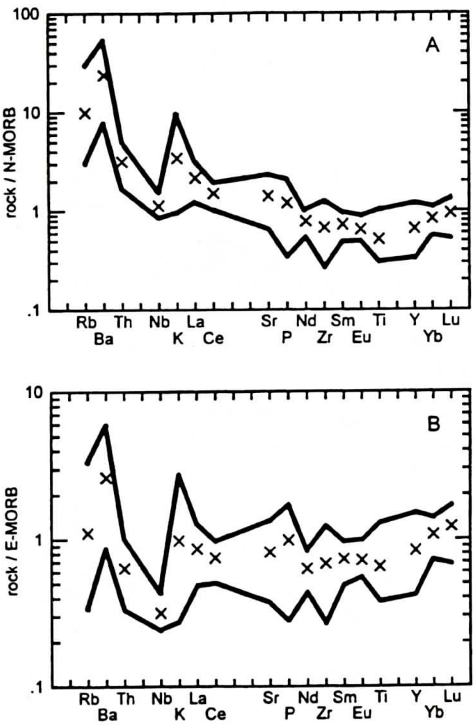

Figure 9. Spidergrams normalized to (A) N-MORBs and (B) E-MORBs for incompatible elements from the Deep River diabases (normalizing factors from Sun and McDonough, 1989). Sources for data are given in the text. Averages are denoted by X's.

which is commonly found in arc-basalts and continental flood basalts (Thompson and others, 1983; Wilson, 1989). Compositional patterns for the Deep River diabases most closely compare with those for incompatible-element enriched (E) MORBs associated with magma plumes and oceanic ridges than normal (N) MORBs associated with oceanic ridges alone (Fig. 9). Significant positive Ba-K and negative Nb anomalies, however, are present for both Figure 9A and 9B. In addition, average La/Yb and Zr/Nb ratios for the Deep River diabases (calculated from data in Table 1) plot in the field for enriched MORBs (Mahoney and others, 1995). Thus in general, trace- and major-element compositions of the Deep River diabases are quite similar in many respects to either E-MORBs or arc tholeiites.

Figures 10 and 11 are summary diagrams for the Nd, Sr, and Pb isotopic systems for the Deep River diabases (data from Pegram, 1986). Whereas MORB compositions (in this case, N-MORBs) are in the +eNd - -eSr field on a Sr-Nd isotopic correlation diagram, those from the diabases are in the -eNd - +eSr field. The field for basalts from Peru, which represents a mature or continental arc, is shown on Figure 10. This field is in contrast to that for the Lesser Antilles, which represents an immature or oceanic arc. The Deep River diabases clearly plot closer to the mature-arc field, although their trend is more similar to the Lesser Antilles trend. The fields for Hawaiian and Servilleta tholeiites within the Rio Grande rift, New Mexico, are also shown on Figure 10. The Hawaiian tholeiites represent oceanic-island basalts, whereas the Servilleta rocks are typical of continental-rift tholeiites.

On a $^{206}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ diagram (Fig. 11), the diabase trend approximately parallels the MORB trend, but at higher $^{207}Pb/^{204}Pb$, more typical of basalts associated with a mature or continental arc. This higher $^{207}Pb/^{204}Pb$ ratio is also typical of most mafic rocks in a continental setting. The Pb-isotopic composition for the Hawaiian Islands overlaps that for N-MORBs, and the field for the Rio Grande (Servilleta) continental tholeiites indicates that they are less radiogenic than the Deep River diabases. The field for these diabases overlaps and falls between that for a mature arc represented by the Carolina terrane and the field representing probably the least radiogenic (granulite facies) composition of Grenville crust.

DISCUSSION

Whether the Deep River diabases more closely resemble MORBs or tholeiites in other tectonic settings can be addressed by turning to their isotopic compositions. Late Paleozoic intermediate and felsic plutons surrounding the Deep River Basin are thought to contain a significant crustal component of both Grenville-age and Late Proterozoic-Early Paleozoic arc volcanics (Samson and others, 1995). The compositional field for these rocks, referred to as

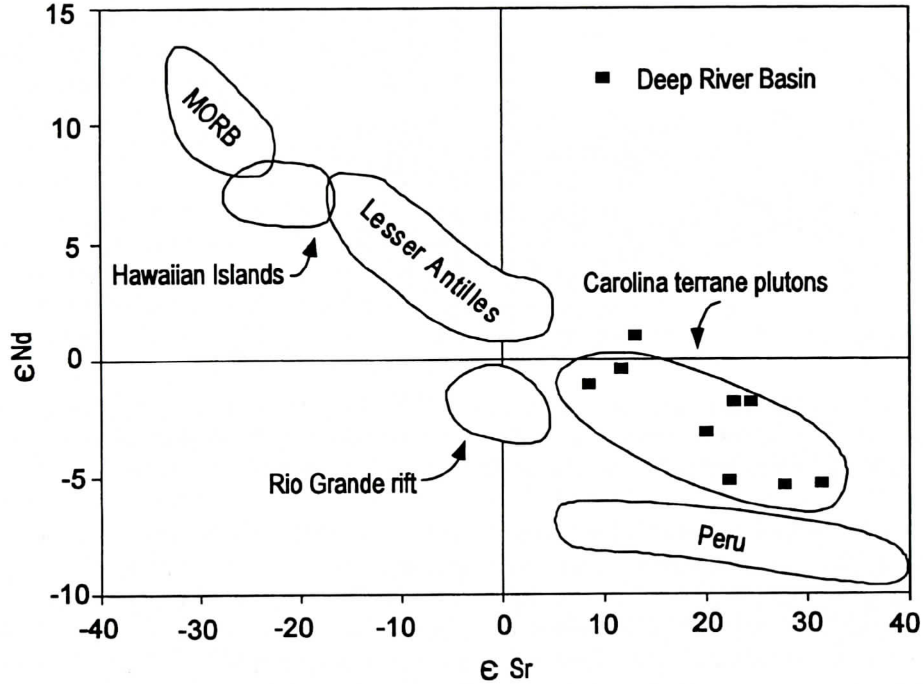

Figure 10. Plot of eSr versus eNd for Deep River diabase dikes in comparison with isotopic compositions of basalts from other tectonic environments (Deep River data from Pegram, 1986).

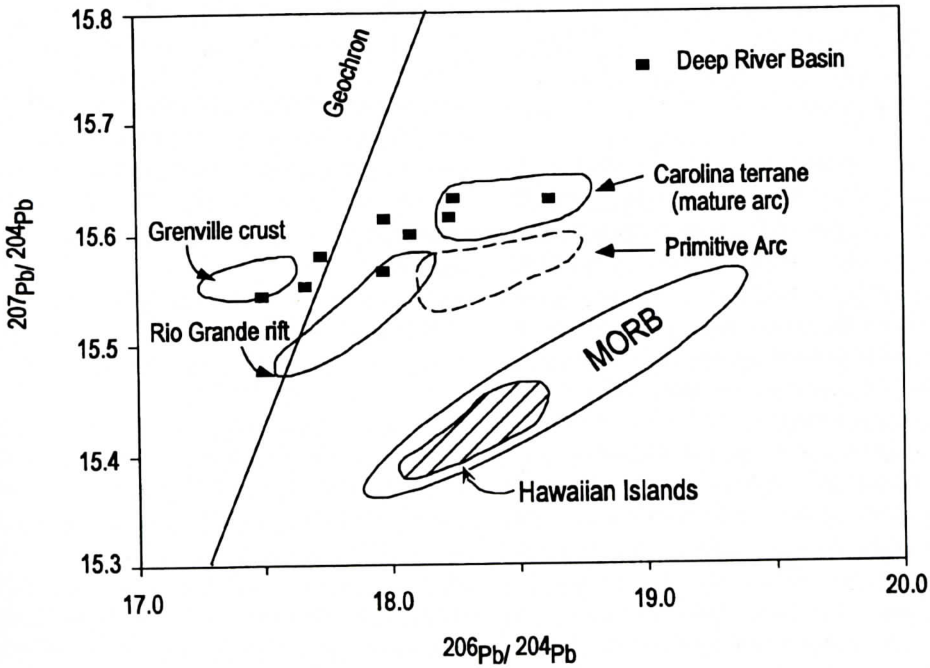

Figure 11. Plot of $^{206}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ for Deep River diabase dikes in comparison with isotopic compositions for basalts from other tectonic environments (Deep River data from Pegram, 1986).

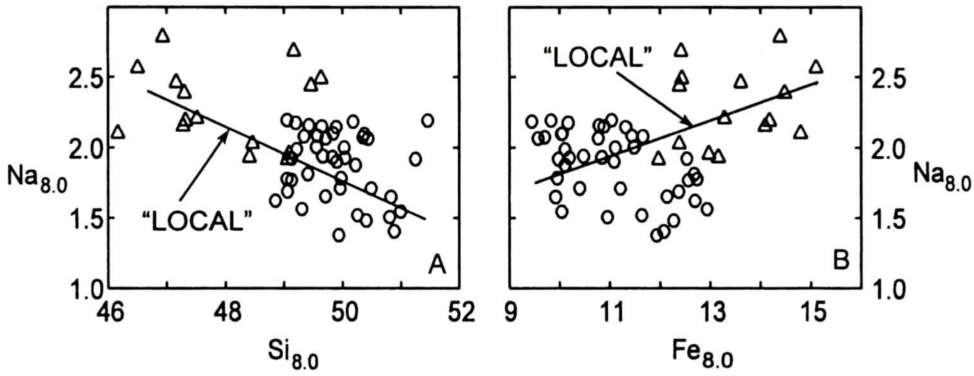

Figure 12. Plots of MgO-standardized concentrations for the Deep River diabases: $Si_{8.0}$ versus $Na_{8.0}$, and $Fe_{8.0}$ versus $Na_{8.0}$. "Local" trends are *not* best-fit lines for the Deep River data, but rather typical local trends for MORBs (Klein and Langmuir, 1989). See text for further explanation.

the Carolina terrane plutons on Figure 10, may approximate the average isotopic crustal composition through which the Deep River basaltic magmas moved. All but one of the Deep River compositions plot within this field.

Thus despite some chemical similarities to MORBs, the isotopic evidence indicates that the Deep River diabases are from a mantle source that had relatively long-term enrichment in incompatible elements such as U and Rb (Pegram, 1986, 1990), or represent some form of crustal contamination of an isotopically MORB-like magma. This contamination is not a bulk contamination and would primarily involve LIL incompatible elements (Fig. 9). A contamination model has been proposed to explain the isotopic characteristics of other rift tholeiites, such as the Rio Grande (Servilleta) tholeiites (Figs. 10 and 11; see also Dugan and others, 1986). Moreover, the negative Nb and Ta anomaly on Figure 8B is commonly interpreted as evidence for crustal contamination (Cox and Hawkesworth, 1985).

Because of phase-equilibria studies (e.g., Stolper, 1980; Jaques and Green, 1980; Fuji and Scarfe, 1985; Kinzler and Grove, 1992a and 1992b), major-element compositions of basalts enable reaching some conclusions regarding mechanisms and physicochemical conditions of mantle melting that lead to the production of basaltic magma. One problem with examining major-element patterns of many basaltic rocks such as diabases is low-pressure fractional crystallization, involving primarily olivine and plagioclase. The chemical trends for the main group in Figure 2 can be explained by such a process. One way to negate this effect of fractional crystallization is to standardize (normalize) the data to some variable that is sensitive to fractionation. For basalts, MgO is commonly used (e.g., Langmuir and others, 1992, and references therein). Major-element MORB compositions have been standardized to 8.0 weight percent MgO (e.g., Klein and Langmuir, 1987, 1989). Variables such as Na_2O, FeO*, and SiO_2 standardized to 8.0 percent MgO (written as $Na_{8.0}$, $Fe_{8.0}$, and $Si_{8.0}$, respectively) have been shown to be particularly useful (ibid.). Two scattergrams plotting these MgO-standardized variables for the Deep River diabases are shown in Figure 12.

The equation used in this paper to standardize the individual analyses to 8 percent MgO (modified after Ragland and Defant, 1983) is:

$$C_S = C_O + m\,(8 - C_{MgO})$$

where C_S is the standardized concentration of the unknown oxide ($Na_{8.0}$, $Fe_{8.0}$, etc.); m is the slope of the MgO-oxide linear-regression line (with MgO as the X variable and the unknown oxide as the Y variable); C_{MgO} is the MgO concentration for that sample; and C_O is the original composition of the unknown oxide.

At the outset of this discussion, the justification for comparing the Deep River diabases to MORBs should be briefly addressed. As reported above, this comparison has frequently been made (e.g., Ragland and others, 1992, and references therein). These diabases are reportedly about 200 Ma (lowest Jurassic) in age; the oldest basaltic sea floor in the Atlantic is Jurassic (Bryan and others, 1977). They were emplaced near the rifting-drifting time boundary during the Pangaean breakup into comparatively thin continental crust. Just how thin is impossible to know, but these rocks almost certainly were the precursors to true MORBs that followed later in the Jurassic. The crust was certainly thicker than oceanic crust through which MORBs ascend, but in our view sufficiently thin for the comparison made in this paper. The isotopic and incompatible-element patterns reported in Figures 8-11 can probably be explained by either Grenville subcrustal, lithospheric slab components in the source region (Pegram, 1986, 1990) or contamination by continental crust. Consequently, although a one-for-one comparison is not valid, comparison of some aspects of the petrogenesis for the Deep River diabases to that for MORBs seems reasonable.

On a global basis, $Na_{8.0}$ and $Si_{8.0}$ for MORBs increase, while $Fe_{8.0}$ decreases, with increasing ridge-axis water depths and decreasing oceanic crustal thicknesses (Langmuir and others, 1992; Klein and Langmuir, 1987, 1989). The reasons for these observations are beyond the scope of this paper (refer to the above references for a complete discussion). They have to do with relatively large and vertically thick mantle-source regions under more shallow mid-oceanic ridges. Within a single ridge segment, however, chemical trends on variation diagrams ("local" trends) are quite different from global trends (Klein and Langmuir, 1989). These "local" trends are explained by differences in degrees of partial melt formed and removed during polybaric partial melting of the mantle column beneath the oceanic ridge. MORBs are assumed to represent aggregates of melt generated at different depths in the mantle. Beneath a single ridge, segment melting starts at similar levels irrespective of the distance from the ridge axis. On-axis melting columns, however, will exist to shallower levels as compared to off-axis melting columns, resulting in a triangular-shaped melting regime (ibid.). Melt aggregates from the off-axis melting columns are generated at comparatively deeper levels and represent smaller degrees of melting, which favor enrichment of Fe and Na relative to Si in the melts (ibid.). Thus these off-axis melt aggregates have higher $Fe_{8.0}$ and $Na_{8.0}$, but lower $Si_{8.0}$, compared to on-axis melts. These differences result in "local" trends exhibiting positive correlations between $Fe_{8.0}$ and $Na_{8.0}$, but negative trends between $Si_{8.0}$ and the other two MgO-standardized elements.

Although chemical patterns in the main-trend diabases (see Fig. 2 and discussion in the Results section) are easily explained, the high-Fe group, recognized throughout much of the southeastern United States, has long been enigmatic with regard to its petrogenesis. For example, Whittington (1988, 1989) invoked fractional crystallization of pyroxene (along with other minerals) to explain this group, but no petrographic evidence can be found to support this hypothesis. No other explanation involving fractional crystallization (high-, intermediate-, or low-pressure), bulk assimilation by crustal materials, or combination of both processes (assimilation-fractional crystallization, AFC) is both mathematically and petrographically reasonable (Ragland, 1991; Ragland and others, 1992). Accordingly, we suggest another possibility.

If the processes that cause mantle melting to produce MORBs can be applied to the Deep River diabases, Figure 12 provides some insight into the relationship between the main-trend and high-Fe groups. Correlations among $Na_{8.0}$, $Fe_{8.0}$, and $Si_{8.0}$ in MORBs for the "local" (as opposed to the "global") situation are quite similar to those shown on Figure 12 for the Deep River diabases. Despite the care taken to choose diabase samples that contain minimal amounts of accumulative phases such as olivine or plagioclase, differential accumulation/ fractionation could account for some of the scatter on Figure 12. Compositions of high-Fe diabases tend to plot on one end of the "local" trends on Figure 12, while the main-trend compositions plot on the other. A speculative suggestion is that the Deep River diabase magmas were formed by a mechanism similar to that reportedly responsible for MORBs. Relative to magmas of the main group, those of the high-Fe group represent deeper levels and smaller degrees of melting.

Finally, the flat pattern and lack of Eu anomalies on Figure 8A suggest that the most likely source for the normal group is an enriched spinel lherzolite. A deeper garnet-lherzolite source would have produced a steeper negative slope to the REE pattern, and a shallower plagioclase-lherzolite source would have produced a negative Eu anomaly.

ACKNOWLEDGEMENTS

The graphics in this paper are done with the 1996 Igpet For Windows (Igpetwin) program of Michael Carr. We are indebted to Vincent Salters for many useful discussions and for reviewing parts of this manuscript. The thoughtful reviews of Ron Fodor and Greg McHone are also very much appreciated. Rosemarie Raymond drafted the map showing the Deep River diabase dikes. Most of the chemical analyses used for this paper were determined by the senior author's students (Paul Drez, B. J. Pegram, Peter Weigand, David Whittington). Their help is gratefully acknowledged.

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SOUTHEASTERN GEOLOGY
V. 38, No. 2, December 1998, p. 103-116

BRITTLE FAULTING ALONG THE WESTERN EDGE OF THE EASTERN NORTH CAROLINA PIEDMONT

MATTHEW J. HELLER

North Carolina Department of Environment and Natural Resources
Mooresville, North Carolina 28115

WILLIAM S. GRIMES AND EDWARD F. STODDARD

Department of Marine, Earth and Atmospheric Sciences
North Carolina State University
Raleigh, North Carolina 27695-8208

DAVID E. BLAKE

Department of Earth Sciences
University of North Carolina - Wilmington
Wilmington, North Carolina 28403-3297

ABSTRACT

Twenty-two map-scale brittle faults and linear cataclastic zones have been identified during separate 1:24,000-scale mapping projects in Wake and Vance Counties, North Carolina. These faults and cataclastic zones overprint late Paleozoic structures and penetrative fabrics that formed in pre-existing Neoproterozoic- to Paleozoic-age crystalline rocks of the eastern Piedmont during Alleghanian orogenesis. Wake County faults and cataclastic zones range up to 13 km in length, and trend N5°E to N10°E and N70°E to N70°W. Vance County faults and cataclastic zones range up to 15 km in length and have trends of N5°E to N10°E, N30°E to N60°E, and N80°E to E-W. Faults and cataclastic zones in both areas have dip magnitudes ranging from approximately 50° to 90°. Lateral separations of crystalline lithodemic units as great as 410 m have been identified across five faults in Wake County and one fault in Vance County. Limited slickenline data along two Wake County faults and two Vance County faults provide evidence that the displacement along those faults was predominantly dip-slip. Apparent truncation of the Falls Leucogneiss in southern Wake County and a sharp metamorphic grade change coincident with the trace of a fault in southern Vance and Granville Counties are compatible with significant dip-slip displacement. Rebrecciated textures preserved in cataclastic rocks suggest recurrent movement along some faults. The orientations and overprinting relationships of dip-slip faults in Wake and Vance Counties suggest that WNW-ESE extension and N-S extension were components of post-Alleghanian deformation along the western edge of the eastern North Carolina Piedmont.

INTRODUCTION

Map-scale brittle faults and cataclastic zones that overprint Paleozoic rock fabrics and structures are well documented in crystalline rocks of the Blue Ridge, Inner Piedmont and Charlotte belts of western North Carolina, South Carolina and Georgia (Hatcher, 1974; Garihan and others, 1990; Preddy, 1991; Garihan and others, 1993; Bartholomew and others, 1997a). Map-scale brittle faulting has also been identified in the Triassic Deep River Basin (Bain and Harvey, 1977; Parker, 1979; Wooten and others, 1996; Wooten and others, 1997; Bartholomew and others, 1997b). Prior to this study, the identification of these structures in crystalline rocks in the eastern Piedmont of North Carolina was limited. Carpenter (1970) mapped two N50ºE-trending cataclastic zones in northern Granville County: a 5 km by 0.3 km zone and a 500 m by 200 m zone. McDaniel (1980) identified 12 N- to NE-trending cataclastic zones during reconnaissance mapping in Vance, Franklin and Warren Counties. Parker (1979) described the NE-trending Jonesboro fault which forms the eastern boundary of the Durham sub-basin of the Deep River Triassic basin during 1:100,000-scale mapping in Wake County.

Since 1982, a significant portion of the eastern North Carolina Piedmont has been mapped at a scale of 1:24,000. The area includes rocks exposed to the east of the Mesozoic Durham sub-basin and west of the late Paleozoic Rolesville batholith (Figure 1). The results of detailed mapping described in this paper (Stoddard, 1996; Stoddard and Heller, 1996; Heller, 1996; Blake, 1997; Grimes, in progress) document the nature and geometry of faults and cataclastic zones in two separate areas. The structural data provide evidence that brittle deformation locally plays an important role in the geologic history of the crystalline rocks.

In southern Wake County, a majority of the brittle faults and cataclastic zones are concentrated along, and parallel to the Swift Creek bluffs, south of Lake Wheeler. Two E- to NE-oriented brittle faults have been mapped in the vicinity of Cary, North Carolina. In southern Vance County, 50 km to the north, cataclastic zones form high, discontinuous ridges having up to 50 m of relief. The most conspicuous ridge system in southern Vance County is a manifestation of a NE-trending extension of the eastern border fault of the Durham sub-basin. The trends of faults and cataclastic zones in both areas are consistently marked by occurrences of vuggy quartz and zones of silicification, cataclasite and breccia (fragments > 5 cm). This paper describes the character of brittle faults in both areas and associated mesoscale brittle structures, and their effects on the surrounding crystalline rocks. As mapping continues in the eastern North Carolina Piedmont, the identification of additional faults and cataclastic zones is likely.

GEOLOGIC SETTING

Crystalline rocks along the western edge of the eastern North Carolina Piedmont are assigned to five Neoproterozoic to Cambrian-age tectonostratigraphic terranes (Figure 1; Horton and others, 1991; Stoddard and others, 1991; Goldberg, 1994; Horton and Stern, 1994) which include the Raleigh, Crabtree, Carolina, and Spring Hope terranes and the Falls Lake Melange. All five terranes have been assigned to the Carolina zone (Figure 1), a first-order fragment of exotic crust that was accreted to the Laurentian margin by the late Paleozoic era (Hibbard and Samson, 1995). Rocks of the Carolina zone in the eastern North Carolina Piedmont largely have felsic or mafic plutonic to volcanic and clastic sedimentary protoliths of oceanic arc affinity (Stoddard and others, 1991).

Carolina zone rocks have also been intruded by felsic and mafic plutons having middle to late Paleozoic ages. All of the Neoproterozoic- to Cambrian-age rocks and a majority of the younger intrusive bodies were subjected to greenschist to amphibolite facies regional metamorphism and penetrative deformation during Alleghanian orogenesis (Farrar, 1985; Russell and others, 1985). These rocks were later intruded by unmetamorphosed diabase dikes thought to be Jurassic in age (De Boer, 1967; Sutter, 1976; Ragland, 1991).

Four ductile structures, the Falls Lake and Leesville faults, the Raleigh antiform, and the Nutbush Creek Fault Zone (NCFZ) form terrane boundaries and/or control map patterns along the western edge of the eastern North Carolina Piedmont (Parker, 1979; Stoddard and others, 1994; Druhan and others, 1994; Blake, 1997). A penetrative regional foliation, generally having a N- to NE-strike, is present in the rocks of all five terranes. Penetrative structures and fabrics have been overprinted by major and minor faults and zones of cataclasis, non-penetrative joints and extension fractures. These structures are generally unmineralized, except that some contain quartz and hematite. For the most part, their age is not known. Similar structures in other parts of the southern Appalachian

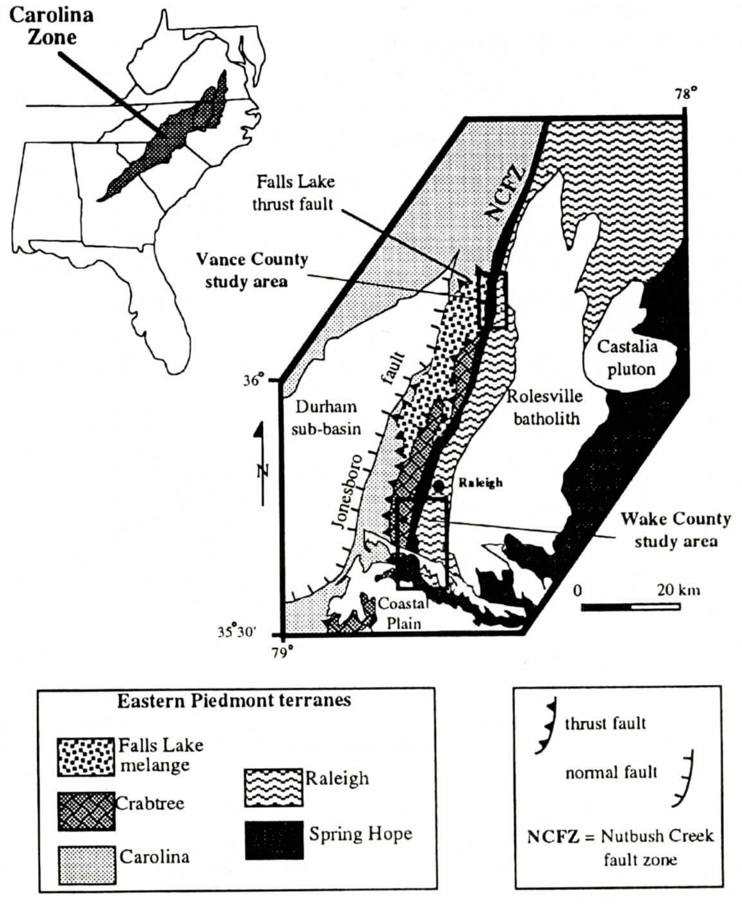

Figure 1. Terrane map of the eastern North Carolina Piedmont (Horton and others, 1994) showing the location of the southern Wake County and southern Vance County study areas. Boundaries for the Carolina Zone inset are those of Hibbard and Samson (1995).

Piedmont have been demonstrated to have Mesozoic to early Cenozoic ages (Olsen and others, 1989, Garihan and Ranson, 1992; Wooten and others, 1997; Bartholomew and others, 1997a). The most significant non-penetrative brittle structure in the eastern Piedmont is the Jonesboro fault, which defines the western edge of the eastern North Carolina Piedmont (Parker, 1979).

BRITTLE FAULTS AND CATACLASTIC ZONES

For the purpose of discussion, curvi-planar brittle discontinuities are grouped as faults and cataclastic zones. Faults are those cataclastic zones along which movement is clearly indicated by slickenlines or visible or inferred separation of wall rocks. The true slips along the faults described in this paper are unknown. Observed horizontal separations represent apparent offsets. Limited slickenline data provide evidence for the sense, but not the magnitude of displacement.

Southern Wake County Faults and Cataclastic Zones

Occurrence

Nine macroscale brittle faults and cataclastic zones have been identified in the Lake Wheeler 7.5-minute quadrangle (Figure 2). Two addi-

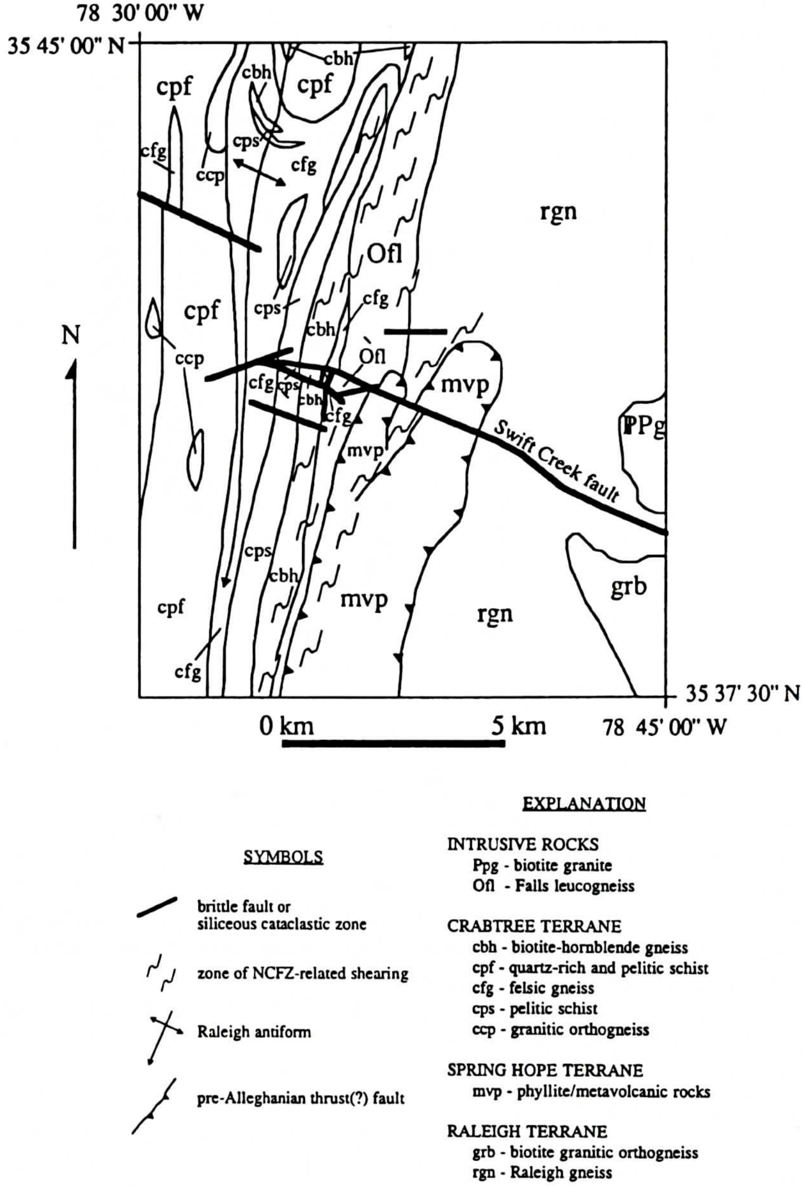

Figure 2. Geologic map of the southern Wake County study area, encompassing the Lake Wheeler 7.5-minute quadrangle, showing map-scale brittle faults and cataclastic zones (Heller, 1996; Stoddard and Heller, 1996).

tional brittle faults have been identified in the Cary 7.5-minute quadrangle. Mapping in progress in the Cary and Apex 7.5-minute quadrangles indicates the presence of additional cataclastic zones, which lie between the Lake Wheeler quad and the Jonesboro fault (Blake, in progress).

These faults and cataclastic zones overprint Neoproterozoic crystalline rocks of the Carolina, Crabtree, Raleigh and Spring Hope terranes, as well as the 491 Ma Falls leucogneiss (Horton and Stern, 1994). Seven of these faults and zones are concentrated as a reticular network south of Lake Wheeler. *In situ* exposures along fault and cataclastic zone trends in the area are rare; the faults and cataclastic zones are most commonly manifest as ridge-top float of vug-rich quartz. Less commonly, float of fault rock consists of siliceous cataclasite or breccia. Topographic expression is generally subtle to nonexistent, with the exception of faults and zones nearest to the south shore of Lake Wheeler. These faults and cataclastic zones are roughly parallel to steep, discontinuous bluffs having up to 25 m of relief.

Orientation

Wake County brittle faults and cataclastic zones may be grouped into three sets based on their general strike and dip attitude. Two cataclastic zones trend N5°E to N10°E. The westernmost and easternmost of these zones, respectively, have been traced for approximately 0.5 km and 1 km. The dip attitude of both of these zones is unknown.

Two faults comprise a second set. The faults trend N70°E to N80°E. They are both moderately N-dipping (about 50° to 60°), where they can be observed in outcrop. The easternmost fault of set II is approximately 2 m wide, where observed; it has been traced for approximately 1 km. The width of the westernmost fault in this set is unknown; it has been traced for approximately 2 km.

Six faults and one cataclastic zone comprise set III. Four faults lie in the vicinity of Lake Wheeler while two others are located near the City of Cary. The structures near Lake Wheeler have N70°W to east-west trends and are subvertical, where observed in outcrop. The largest member of the third set is approximately 5 m wide and has been traced for over 13 km; it extends eastward into the Garner 7.5-minute quadrangle. The Swift Creek fault is proposed here as a name for this significant structure because it is roughly parallel to that drainage. In southeast and northeast Cary, two faults, oriented N80°E and E-W, respectively, have unknown thicknesses. The attitudes of the Cary faults are unknown. They are tentatively grouped with set III faults on the basis of mapped horizontal separations of Carolina terrane lithodemic contacts. Mappable horizontal separations have not been observed along set II faults.

Displacement

Left- and right-lateral horizontal separations of variably dipping rock units have been mapped along all six set III WNW-trending faults; separations ranging up to 390 m have been inferred. For the three southernmost set III WNW-trending faults on the Lake Wheeler 7.5-minute quadrangle along the east-dipping limb of the Raleigh antiform, these horizontal separations alternate from dextral to sinistral to dextral, from north to south. Alternating dip-slip displacement, indicative of a graben and horst structure (from north to south), may explain the alternating horizontal separations. However, because slickenline data are not available for set III faults, no resolution of actual dip-slip, strike-slip, or oblique-slip motion is possible.

Dip-parallel slickenlines observed at a single exposure along each set II fault in southern Wake County suggest dip-slip displacement along those faults. No horizontal separations of rock units have been identified along set II faults. The easternmost set II fault juxtaposes Falls Leucogneiss against felsic gneiss of the Crabtree terrane, suggesting significant displacement. *In situ* exposures of NNE-trending set I cataclastic zones have not been encountered. Vuggy quartz and cataclasite have been observed as float along their trends.

Southern Vance County Faults and Cataclastic Zones

Occurrence

Three faults and eight cataclastic zones have been identified in the Kittrell 7.5-minute quadrangle (Figure 3). These faults and cataclastic zones overprint rocks assigned to the Raleigh terrane and the Falls Lake melange, as well as the Falls Leucogneiss. *In situ* exposures along a N35°E trending fault and along one N5°E trending fault in the Kittrell quadrangle have been located; nine additional N5°E to N10°E, N30°E to N60°E, and N80°E to E-W trending faults and cataclastic zones are expressed by ridge-top float. As in the Lake Wheeler area, ridge-top float in the Kittrell quadrangle commonly con-

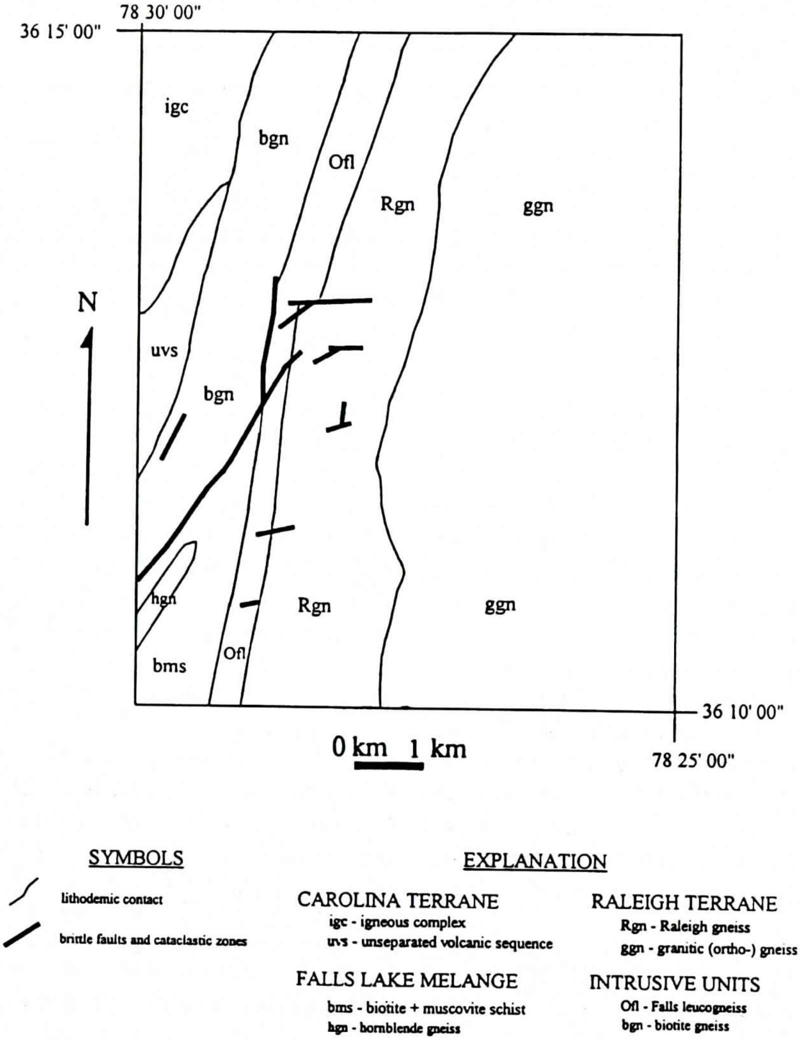

Figure 3. Geologic map of the southern Vance County study area, a portion of the Kitrell 7.5 minute quadrangle, showing map-scale brittle faults and cataclastic zones (Grimes, in progress).

sists of vuggy quartz boulders, having lesser amounts of cataclasite and breccia. Topographic expression of these brittle features is strong; they form linear topographic highs, ridge tops and steep bluffs having up to 50 m of relief.

The N35°E-trending fault is an extension of siliceous cataclasite mapped by Carpenter (1970); a change in metamorphic grade that is approximately coincident with this fault (Farrar, 1985; Blake, 1986) suggests significant displacement. In the Kittrell area, this extension is informally called the Little Egypt fault for exposures on Little Egypt Mountain. The Little Egypt fault can be traced from Little Egypt Mountain for 10 km southwest into the Wilton 7.5-minute quadrangle where it cuts the western edge of the 285 Ma Wilton pluton (Carpenter, 1970; Fullagar and Butler, 1979), and for approximately 5 km further southwest to its junction with the Mesozoic Jonesboro fault. This splay of the Jonesboro fault constitutes the largest post-Alleghanian feature affecting crystalline rocks of the eastern North Carolina Piedmont. Other faults and cataclastic zones in this area are relatively minor and can be traced for distances from 500 m to approximately 2 km. Fault and cataclastic zone widths are poorly constrained; they may range up to 100 m based upon ridge-top float distribution.

Orientation

Faults and cataclastic zones in southern Vance County may also be grouped into three sets. One fault, informally called the Tabb's Creek fault because it roughly parallels that drainage, and one cataclastic zone have N5°E and N10°E trends, respectively. The Little Egypt fault and three cataclastic zones have N30°E to N60°E trends. One fault and four additional cataclastic zones have N80°E to east-west trends. Where observed, both the Tabbs Creek and Little Egypt faults have sub-vertical dips. The attitudes of several other faults and cataclastic zones are unknown.

Displacement

An observed 410 m right-lateral horizontal separation of the contact between the Falls leucogneiss and Neoproterozoic- to Cambrian-age Raleigh Gneiss has been observed in the Kittrell area (Grimes, in progress). This observed separation occurs across a set III fault having a N85°E trend. No *in situ* exposures of this fault have been identified, making displacement determinations impossible. The complex nature of lithologic interlayering within the Falls Lake melange and the Raleigh terrane makes the identification of map-scale offsets along brittle faults difficult.

Slickenlines having dip-parallel plunges have been observed along the Little Egypt and Tabbs Creek faults, and suggest that dip-slip displacement was dominant. Evidence for significant dip-slip displacement has been identified along the Little Egypt fault where, in northern Granville County, it appears to juxtapose greenschist facies Falls Lake melange to the northwest, with amphibolite facies Falls Lake Melange, to the southeast (Carpenter, 1970; Farrar, 1985; Blake, 1986; Stoddard and others, 1994). In addition, the map pattern of the Wilton pluton in the Kittrell quadrangle is truncated by the Little Egypt fault (Carpenter, 1970), also suggesting significant displacement.

PETROGRAPHY OF CATACLASTIC ROCKS

Three distinct types of cataclastic rocks which include vuggy quartz, cataclasite, and breccia, have been observed along the trends of brittle faults and cataclastic zones in both Wake and Vance Counties. Vuggy quartz is by far the most common rock associated with faults and cataclastic zones. Vuggy quartz is similar in appearance to the white, massive "bull" quartz that is common in the eastern North Carolina Piedmont. Vuggy quartz contains sparse to abundant irregularly shaped cavities that are often lined with drusy, commonly euhedral quartz crystals ranging up to 5 cm in length. Less commonly, aggregates of subhedral quartz crystals are observed (Figure 4a). Vuggy quartz is often associated with bull quartz, cataclasite and breccia along fault trends. Cataclasite is light pink to dark tan in color. It often has a mottled appearance and is very fine grained (Figure 4b).

Both monolithic and polylithic breccia have been observed along faults and cataclastic zones. In southern Wake County, saprolitic exposures of monolithic breccia may contain up to 70% weakly oriented to unoriented angular clasts of local wall rocks supported by a fine-grained, clay rich matrix (Figure 4c). In saprolite exposures east of Lake Wheeler along a south-flowing tributary to Swift Creek (35°41'45"N, 78°40'50"W), a transition from unaffected Raleigh terrane granitic gneiss, to highly fractured granitic gneiss to monolithic breccia is observed across a distance of 10 m.

Polylithic breccia has been observed along the Swift Creek fault on the south shore of Lake Wheeler (35°41'15"N, 78°42'00"W), in Vance County along the Tabbs Creek fault (36°12'33"N, 78°28'15"W) and along an unnamed zone along a NW-trending tributary to Coles Branch in western Cary (35°47'30"N, 78°47'30"W). Breccia at these locations contains up to 40% rock fragments that range from <1 cm to >5 cm in diameter. Fragments are chemically weathered and angular, and they are cemented by massive to crystalline quartz. Some fragments in breccia along the Swift Creek fault appear to be similar in composition

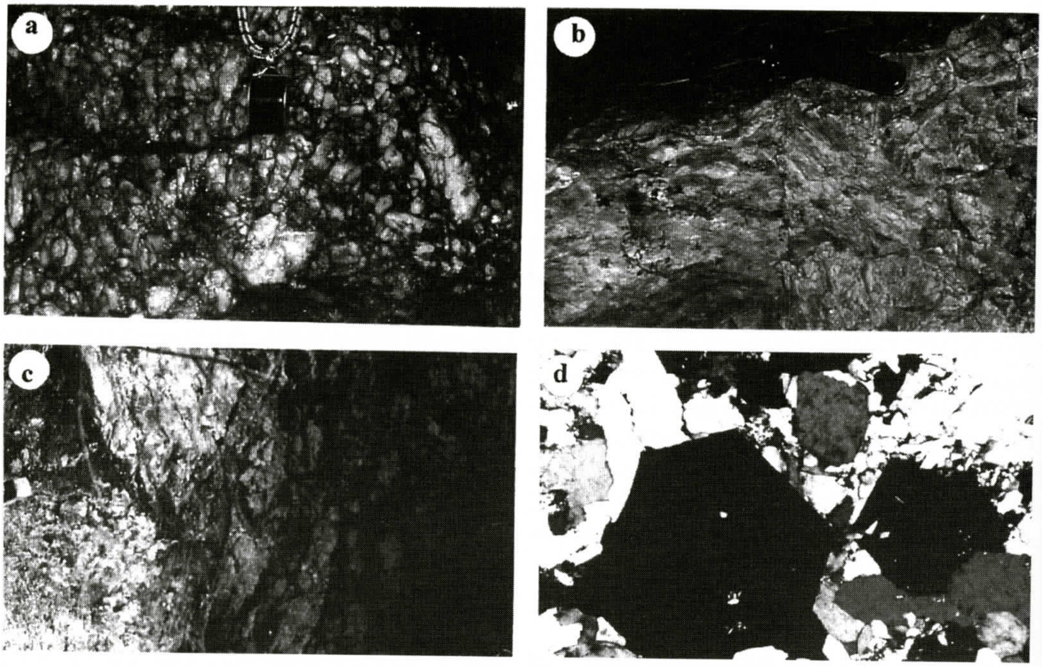

Figure 4. Fault-related rocks: (a) float consisting of randomly oriented, intergrown subhedral quartz crystals, hand lens for scale; (b) siliceous cataclasite with mottled appearance and visible fractures, pocketknife for scale; (c) monolithic breccia containing angular fragments of granitic gneiss (light colored rock), hammer head at bottom of photo for scale and photograph oriented 90° to other photographs for viewing purposes; (d) photomicrograph of euhedral quartz crystals cemented in the fragmented quartz matrix of a polylithic breccia, cross-polarized light, photomicrograph width is 0.5 mm. Section cut approximately perpendicular to c-axes of euhedral crystals. Angular quartz inclusions in euhedral crystal may indicate growth, or continued growth, after brecciation (or an earlier period of brecciation).

and texture to Falls Leucogneiss which is the wall rock along this part of the fault. Some clasts along both the Swift Creek and Tabbs Creek faults appear to be lower grade felsic metavolcanic rocks. These fragments may represent material displaced along the faults, possibly derived from structurally higher levels of the Crabtree, Carolina or Spring Hope terranes.

Rebrecciated textures in polylithic breccia including angular fragments of cemented quartz and breccia and euhedral quartz crystals within cemented matrix are used as evidence to indicate repeated movement along the set III Swift Creek fault (Figure 4d). The latter are interpreted as crystals which formed in vugs which were then broken during later shearing and incorporated into a newly precipitated anhedral quartz matrix. Evidence for repeated movement along other faults has not been observed. Similar rebrecciated textures have been observed in brittle faults by workers in other parts of the southern Appalachian Piedmont (Conley and Drummond, 1965; Garihan and others, 1993; Bartholomew and others, 1994).

TIMING OF MOVEMENT ALONG FAULTS

The absolute ages of brittle faults and cataclastic zones in southern Wake and Vance Counties are not well constrained. These structures do disrupt and therefore postdate the penetrative regional foliation in rocks of the Neoproterozoic Carolina, Crabtree, Spring Hope, and Raleigh terranes, the Falls Lake melange and middle- to late-Paleozoic age intrusive bodies. ^{40}Ar/ ^{39}Ar cooling ages of 320 Ma (for hornblende; closure temperature 500° C) and 240-270 Ma (for micas; closure temperatures 350° to 300° C) have been reported for minerals aligned with the regional foliation in the western part of the eastern Piedmont (Russell and others, 1985). Faults in both Wake and Vance Counties also offset discrete shear zones and fabrics associated with the 312 to 285 Ma Nutbush Creek fault zone. The southwestward extension of Little Egypt fault also offsets the unsheared, non-foliated 285 Ma (Fullagar and Butler, 1979) Wilton pluton (Carpenter, 1970).

The brittle nature of the deformation which produced the faults and cataclastic zones, combined with a lack of associated mineral growth, suggests that the deformation occurred under metamorphic conditions different from those that existed during peak Alleghanian orogenesis. The Little Egypt fault in fact, is thought to be the NE-extension of a splay of the Jonesboro fault. Movement along the Jonesboro fault formed a half-graben into which Triassic sediments were deposited (Parker, 1979; Hoffman and Gallagher, 1989). The stratigraphy of the basin suggests that the Jonesboro fault was active 40 to 50 million years after the Alleghanian Orogeny (Olsen and others, 1989).

Intersections between the Wake and Vance County faults and regional diabase dikes thought to be Jurassic in age (De Boer, 1967; Sutter, 1976) have not been observed in outcrop. Diabase dikes intrude sedimentary rocks in the Triassic Durham sub-basin and have been mapped or shown by geophysical methods to be offset by brittle faults in the Durham sub-basin near Shearon Harris Lake, and by the Jonesboro fault, in western Wake County (Ebasco Services, Inc., 1975; Bain and Harvey, 1977). It is likely, therefore, that the period of emplacement of diabase dikes occurred after the initial movement along the Jonesboro fault, and prior to latest motion along the Jonesboro fault and other brittle faults in that area. No horizontal separation of either the faults or the dikes has been inferred during mapping. Therefore, the relative age of the diabase dikes to other faults and cataclastic zones reported here in crystalline rocks to the west of the Durham sub-basin is unknown.

In southern Wake County, relative ages among faults and cataclastic zones are not consistent. South of Lake Wheeler, a set III fault (N70°W to east-west) appears to truncate a set II (N70°E to N80°E) fault and a NNE-trending set I (N5°E to N10°E) cataclastic zone, while another set III fault appears to be truncated by a different set II fault and by the same set I cataclastic zone. In Vance County, observed map patterns among faults and cataclastic zones show more consistent relationships. Three different set III (N80°E to E-W) cataclastic zones appear to truncate two set II (N30°E to N60°E) cataclastic zones and one set I (N5°E to N10°E) cataclastic zone. Also, the set II Little Egypt fault appears to truncate the set I Tabbs Creek fault, suggesting that it is younger.

ASSOCIATED STRUCTURES

Minor faults

Minor faults have been previously reported in the eastern Piedmont (Parker, 1979). These features have also been observed at a few locations near larger faults in southern Wake and Vance Counties. Minor fault widths are generally on the order of a few mm (Figure 5a). They are generally straight and planar, and typically traceable for a few meters. In both the Wake and Vance County areas, dipping compositional layers and regional foliations having left lateral horizontal separations that range up to 5 cm in length are common. Minor fault orientations are similar to those of larger faults and cataclastic zones.

Extension fractures

Quartz- and epidote-filled fractures are common adjacent to and within faults and cataclastic zones. The quartz- or epidote-filling is usually massive. Locally euhedral quartz crystal fillings grow towards fracture centers (Figure 5b). Extension fractures in the country rocks tend to be planar and parallel to adjacent faults. These data support extension adjacent to faults in both areas. Extensional fractures within the faults and cataclastic zones are typically arcuate

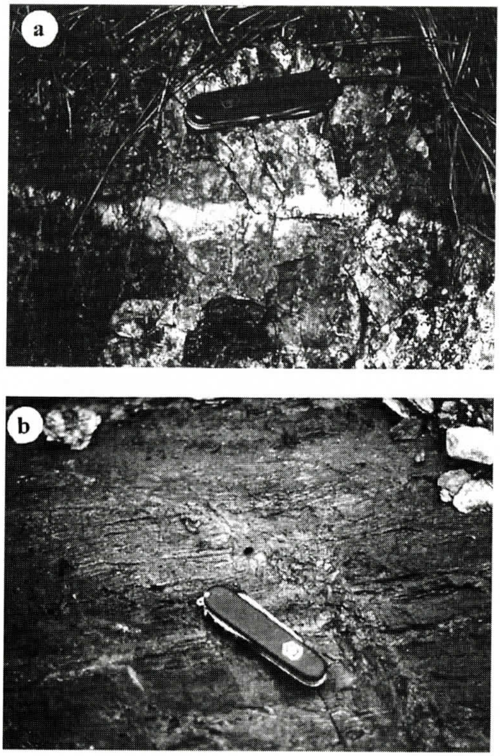

Figure 5. Associated minor structures: (a) quartz fracture in highly fractured Crabtree terrane felsic gneiss showing euhedral quartz crystal filling, pocketknife for scale; (b) monolithic breccia developed along minor fault in saprolitic Spring Hope terrane metavolcanic rock, pocketknife for scale.

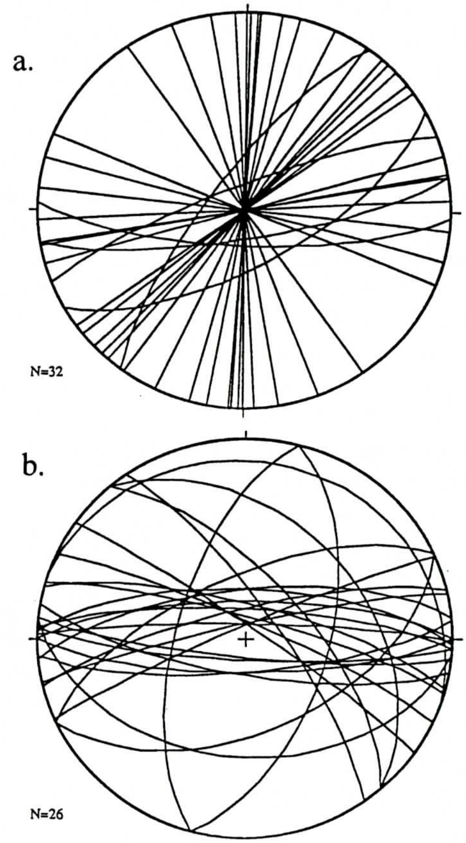

Figure 6. Equal area stereographic projections showing the orientations of unmineralized joints in (a) Wake County, using the data of Heller (1996) and Welby and Wilson (1982), and (b) southern Vance County, using the data of Grimes (in progress).

and have variable orientations.

Joints

The majority of joints in the Lake Wheeler area are sub-vertical and strike either roughly north-south, roughly NE-SW, or roughly east-west (Figure 6a). Similar joint orientations have been reported during regional mapping (Parker, 1979; Welby and Wilson, 1982) in Wake County. The majority of joints in the Kittrell area strike east-west and are moderate to steep (Figure 6b). The joints observed during this study are planar, spaced and unmineralized. Joints become more common and joint spacing decreases adjacent to faults and cataclastic zones. Joints in the country rocks near larger faults and zones are dominantly subparallel to the fault or zone trend.

The similar orientations of faults and joints in both Wake and Vance Counties suggest that their formation is related in some way. The relative ages of these structures to one another cannot be determined with available data. It is possible that the faults formed preferentially along pre-existing joint sets, as proposed by Garihan and Ranson (1992) for brittle faults in the Marietta-Tryon basin. The decreased spacing and dominantly parallel orientation of joints in country rocks adjacent to set I and set II faults in southern Wake County, however, suggest that the joints and the faults in that area may have formed at the same time, in response to the same regional state of stress.

DISCUSSION

Moderate to steep brittle faults having normal to oblique-normal displacement have been reported in the Inner Piedmont and Charlotte belts of Georgia, South Carolina and North Carolina (Preddy, 1991; Garihan and others, 1993), in Alleghanian granites and overlying sedimentary rocks in the Atlantic Coastal Plain of South Carolina and Georgia (Bartholomew and others, 1997a) and in the Durham sub-basin (Wooten and others, 1996; Wooten and others, 1997; Bartholomew and others, 1993; Bartholomew and others, 1997a). The reported orientations of faults in the Durham sub-basin in southwestern Wake County (N-S to N30°E and east-west to N72°W; Wooten and others, 1996; Bartholomew and others, 1997b) are strikingly similar to those we report in the crystalline rocks in southern Wake County, approximately 35 km to the east. Stresses responsible for brittle deformation may be regional in nature.

NNE- and NE-trending faults and cataclastic zones identified in southern Vance County appear to be truncated by, and therefore pre-date, roughly east-west trending faults and cataclastic zones. The NE-trending Little Egypt fault itself is really an extension of the NNE- to NE-trending Durham segment of the Jonesboro fault, which has documented normal to sinistral-oblique normal displacement along its trace to the southwest, in Wake County (Parker, 1979; Bartholomew and others, 1994). Dip-parallel slickenlines, a metamorphic grade change coincident with the fault trace and the truncation of the Wilton pluton support a normal component of displacement along this fault in southern Vance County as well. Predominantly normal displacement is also suggested along the N5°E-trending Tabbs Creek fault by dip-parallel slickenlines. The orientation of the Tabbs Creek fault is similar to that of parts of the Jonesboro fault (Figure 1). We believe that the Little Egypt and Tabbs Creek faults, as well as other set I (N5°E to N10°E) and set II (N30°E to N60°E) cataclastic zones in southern Vance County are contemporaneous with the Jonesboro fault, forming in response to roughly WNW-ESE extension. The difference in orientation between set I and set II faults and cataclastic zones may be the result of preferential development of set I faults and cataclastic zones along regional foliation surfaces and lithologic contacts. The Tabbs Creek fault, for instance, is coincident with the contact between the Falls Leucogneiss and rocks of the Raleigh terrane, strongly suggesting tectonic heredity. Antecedent structures may also be responsible for set I (N5°E to N10°E) cataclastic zones in southern Wake County which trend parallel to the regional foliation; whether or not these cataclastic zones are related to the same period of extension that created the Jonesboro fault is uncertain.

Well developed faults and cataclastic zones having roughly east-west trends have been identified in both Wake and Vance Counties. A normal component of displacement along these faults is suggested by parallel extension fractures and joints, dip-parallel slickenlines and the truncation of crystalline rock units. These faults, cataclastic zones and associated structures collectively suggest one or more periods of north-south extension. In Vance County, set III (N80°E to east-west) faults and cataclastic zones truncate NNE- and NE-trending faults, suggesting this period of north-south extension in southern Vance County overlaps with or postdates displacement along the Jonesboro fault, including the segment informally referred to here as the Little Egypt fault. Whether the roughly east-west trending faults in Vance County are of the same age as those in Wake County is uncertain.

The transition from WNW-ESE extension to roughly north-south extension suggested by data provided here is compatible with chronologies reported by workers in other areas of the southern Appalachian Piedmont. Garihan and Ranson (1992) report a chronology for brittle deformation in the Marietta-Tryon graben, based upon fault displacement data and overprinting relationships, in which NW-SE extension overlapping the period of emplacement of diabase dikes is followed by NE-SW extension.

Bartholomew and others (1997b) propose a post-Alleghanian history for crystalline rocks and overlying Coastal Plain sedimentary rocks in eastern South Carolina and Georgia based upon overprinting relationships among fracture sets. They report periods of north-south and NW-SE to east-west extension prior to the Late Jurassic and periods of N-S and E-W extension after the Late Jurassic. In the Durham sub-basin in southwestern Wake County, Wooten and others (1997) report a chronology based upon overprinting relationships among faults and fractures in which NW-SE extension is followed by NNE-SSW extension. They also report later dextral shearing along a WNW-trending fault. All of these chronologies include approximately 90º rotations in extension directions. These rotations may indicate a shift in the direction of tectonic rifting, or they may indicate a paleostress field in which the minimum and intermediate principal stresses interchanged (Hibbard, personal communication).

SUMMARY

Recent 1:24,000-scale mapping has identified sets of moderate to steep faults and cataclastic zones in two separate areas along the western edge of the eastern North Carolina Piedmont. The type and magnitude of displacement across almost all of the faults described here is not well constrained. A detailed examination of mapped exposures is needed. Available slickenline data, mapped truncations of rock units and a metamorphic grade change coincident with the trace of the Little Egypt fault suggest a component of dip-slip displacement along some faults. Closely spaced extension fractures and joints observed parallel to the trends of these faults suggest that this dip-slip component is normal. This inferred displacement along the NNE- to NE- and approximately east-west trending faults suggests that WNW-ESE extension and roughly north-south extension were components of late brittle deformation in this area. In Vance County, NNE- to NE-trending faults and cataclastic zones appear to be of the same generation as the Jonesboro fault; they are overprinted by ENE- to east-west trending faults. This rotation in extension direction is generally consistent with data collected from areas of concentrated brittle deformation in more southern and western parts of the southern Appalachian Piedmont (Garihan and others, 1993; Wooten and others, 1997; Bartholomew and others, 1997b).

Further study of the non-penetrative brittle and ductile structures here, and in other parts of the southern Appalachian Piedmont is necessary to allow a better understanding of the transition period between the Alleghanian orogeny and the establishment of a trailing edge continental margin along the southeastern edge of the present North American craton. Establishing better constraints on the displacement of Wake and Vance County faults and determining the relative ages of these faults to one another, regional joints, and diabase dikes is critical to better determining how these faults relate to others reported in the southern Appalachian Piedmont.

ACKNOWLEDGMENTS

The authors thank Jack Garihan and Mark Anders for their thorough review of this manuscript and acknowledge the support of the North Carolina Geological Survey's STATEMAP program, which partially funded the mapping that produced this new data.

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